**The Thesis Committee for Renas Ismael Mohammed**
**Certifies that this is the approved version of the following thesis:**

# Distribution and Development of Middle Miocene Submarine Fans, Taranaki Basin, New Zealand

**APPROVED BY**
**SUPERVISING COMMITTEE:**

**Supervisor:**

William L. Fisher

Ronald J. Steel

Brian K. Horton

# Distribution and Development of Middle Miocene Submarine Fans, Taranaki Basin, New Zealand

by

**Renas Ismael Mohammed, BS**

**Thesis**

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# Dedication

To my parents, who sacrificed for me and raised me with a falcon look-a-like passion, always heading toward highs and never give up. Because of them, I am what I am today.

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# Abstract

**Distribution and Development of Middle Miocene Submarine Fans, Taranaki Basin, New Zealand**

Renas Ismael Mohammed, MS. GeoSci.
The University of Texas at Austin, 2011

Supervisor: William L. Fisher

The Taranaki Basin was formed as a consequence of multiple geologic events. From the Cretaceous period until present, it went through rifted margin, passive margin, foreland basin, and back-arc phases. A dominantly sandy unit, the Moki Formation, was deposited during the Middle Miocene within the Taranaki Basin offshore the west coast of the North Island of New Zealand. The study area covers about 1600 $km^2$ of the southern part of the north Taranaki graben, an area covered by a 3D seismic volume. The Moki Formation is interpreted as a basin floor fan deposit that accumulated during basinward migration of the shelf edge with supplied sediments sourced from the SSE.

Seismic profiles revealed that the mound-shape reflectors of Moki fan deposits

situated between continuous reflectors of underlying Oligocene carbonates and hemipelagic muds of the overlying Manganui Formation. The reflections of the Moki sandy fan deposits locally grade laterally into interlobal deposits of hemipelagic muds. Correlation between wells Witiora-1, Taimana-1, and Arawa-1 verified the seismic interpretation, which shows an overall thickness variation of fan deposits that range from a greater thickness in the middle part of the sand lobe accumulation towards diminished thicknesses on the flanks. Gamma ray facies show clear progradation then aggradation motif that confirm the results from the seismic analyses. Depending on seismic attribute maps, paleochannels associated with the sand bodies sharing a SE to NW flow direction can be distinguished. Due to the volcanic activity in the eastern mobile belt, no paleochannels or significant stratigraphic features were recognized within the studied interval of the seismic data. Generally, in the study area, the fan deposits represent sand-rich deposits that developed and prograded from south to north with variations in lateral extent driven by three major shifts in sediment pathways as the feeder channel orientations changed.

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# Chapter 1: Introduction

## 1.1 Preface

The Taranaki Basin is considered one of the major depocenters and the only hydrocarbon-producing basin of New Zealand (Palmer and Bulte, 1991). It is located offshore, adjacent to the Taranaki Peninsula, west of North Island. The deepest part of the basin belongs to the Late Cretaceous and rests on basement rock. The reservoirs that contain hydrocarbons are found in Paleocene to Pliocene sedimentary rocks. In these reservoirs, sandstone is the main host unit.

Throughout the Taranaki Basin history, numerous geologic events contributed to basin evolution and the accumulation of good sandstone reservoirs. The tectonic history began with Gondwana rifting in mid Cretaceous followed by a quiescent era and subsidence. Then in mid Oligocene, convergence of Pacific plate beneath the New Zealand began and formed the foreland. These tectonic stages, as well as relative sea level changes affected the sediments that filled the basin. The Taranaki Basin includes several reservoirs with ages from Late Cretaceous to Early Pliocene and depositional environments vary widely. The depositional environments include, sand and shale mixtures of deep marine, lower alluvial, delta, nonmarine sandstone, barrier bars, submarine fan complex, and outer shelf to upper slope limestones (Ministry of Economic Development of New Zealand, 2010). One of the economically important exploration targets in the stratigraphic succession of the northern Taranaki Basin is the Moki Formation. It is judged to be a basin floor submarine fan deposited during the Middle Miocene.

This study is an attempt to characterize the Moki fan deposits in the northern Taranaki Basin by using 3D seismic and well data. In 2005, Pogo New Zealand conducted 2D and 3D seismic surveys in the western offshore Taranaki area that produced data for new ideas and a better understanding of Taranaki Basin.

This chapter covers the significance of this research, the study location, and previous work conducted by other researchers. Chapter two provides the general geology of the Taranaki Basin with a focus on the tectonic evolution and stratigraphic record. In the third chapter, I explain the depositional environment of the Moki Formation and the methodology involved. In chapter four, I discuss the development and distribution of the Moki Formation in the study area in light of my new interpretations. The final chapter is a presentation of the conclusions revealed in this study.

### 1.2 Motivation

The primary goal of this thesis is to investigate middle Miocene fan deposits of the Moki Formation in terms of the development of the sand-body lobes and their spatial distribution in the northern Taranaki Basin. During middle Miocene deposition, the southern and eastern parts of the Taranaki were a highland area (King and Thrasher, 1996). They acted as a large sediment source area that was progressively eroded. Sediments were transported toward NNW along the shelf and down slope to the basin floor.

## 1.3 STUDY AREA

The Taranaki Basin, a foreland basin, is located west of the North Island of New Zealand (fig. 1.1). Its southern limit begins at the northern edge of the South Island and extends northward to Auckland in the North Island of New Zealand (Pilaar and Wakefield, 1978).

The Parihaka 3D seismic survey covers the area included in this study. It covers 1600 km$^2$ in the middle of the Taranaki Basin, offshore of the Taranaki Peninsula (fig. 1.2). Within the area there are several buried paleovolcano with various ages from the Early Miocene to the present covered by younger sediments. Within and around the 3D seismic study, four wells were drilled that enhance the understanding of the region.

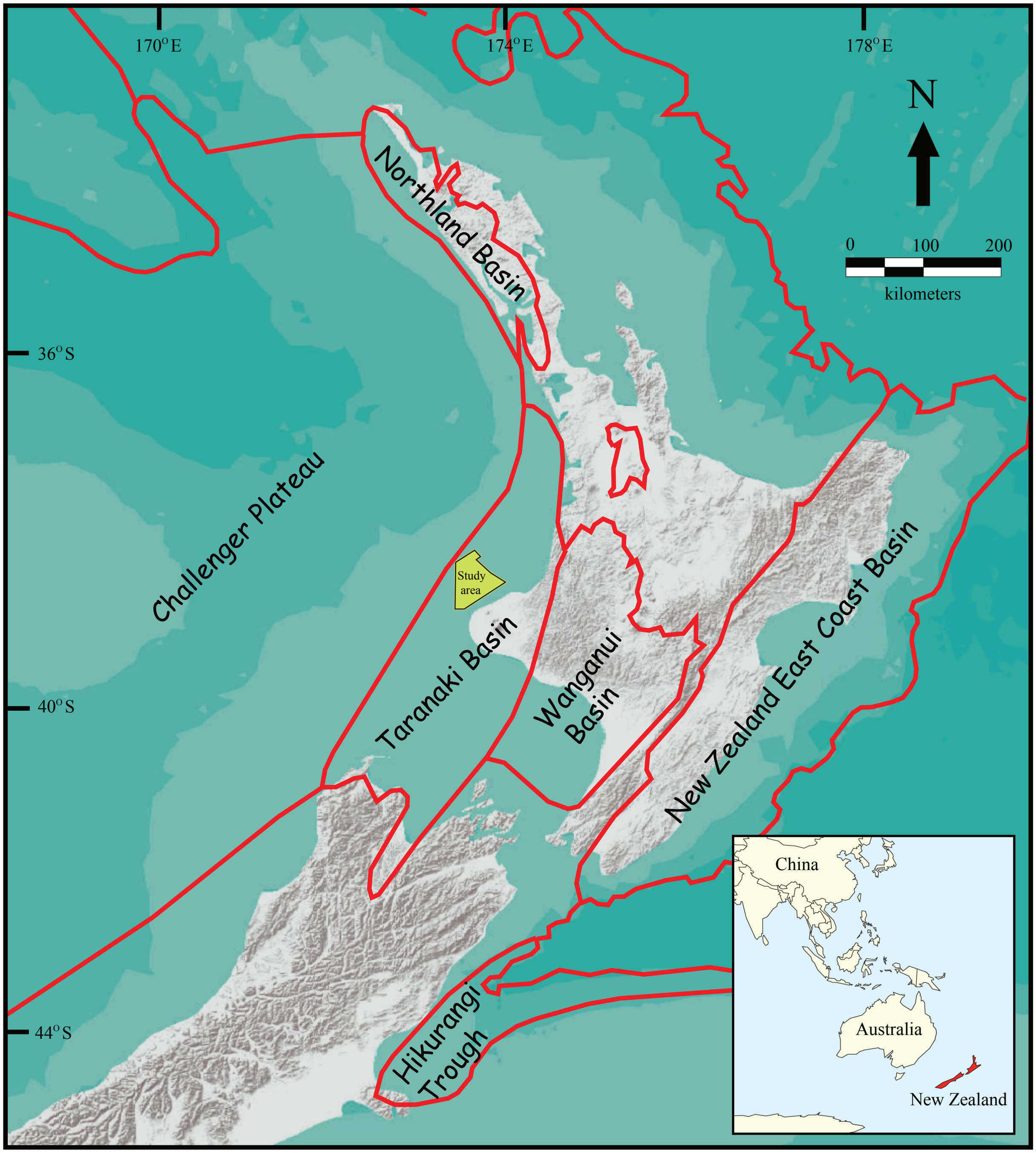



Figure 1.1: New Zealand's geologic provinces. The Taranaki Basin is located at the western edge of the North Island.

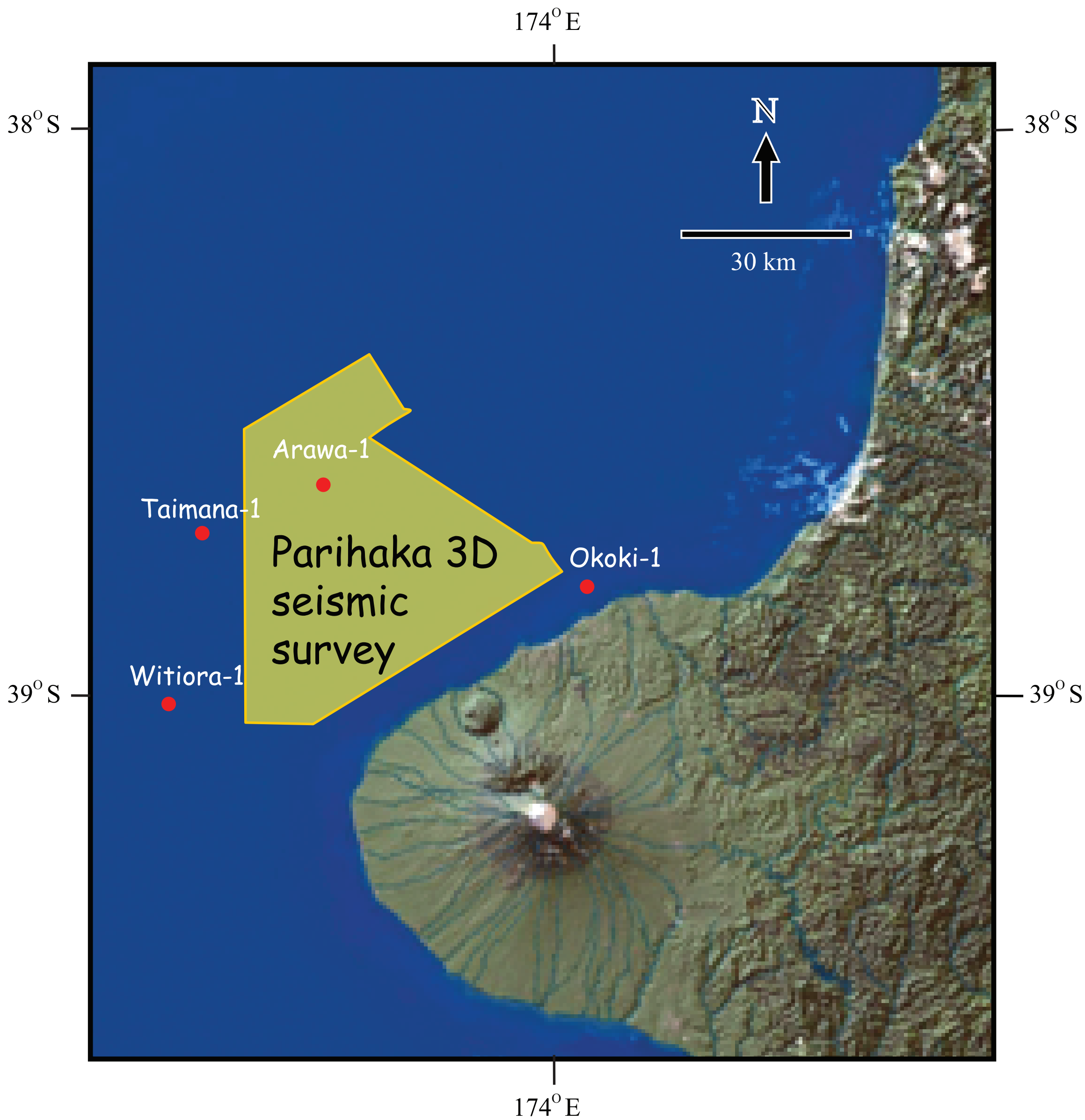



Figure 1.2: The Taranaki Peninsula and location of Parihaka seismic survey and the four wells that are used in this study.

## 1.4 Previous Work

Since the first hydrocarbon discovery in 1970 within the middle Miocene Moki submarine fan deposits, several studies have been published on the submarine fans in Taranaki basin in New Zealand (fig. 1.3). Until mid 1990s, the Moki sandstone reservoir was believed to contain noncommercial amounts of hydrocarbon as tested by Maui-4 in 970 and Moki-1 in 1983 (Dauzacker et al., 1996). More recent research and reinterpretations of previous data (Engbers, 2002) have guided the understanding of the Middle Miocene submarine fan.

The term "Moki" Formation was introduced by Lock (1985) to characterize the Middle Miocene sandstone of the Taranaki Basin, replacing the Mokau Group in the Taranaki Basin (King and Thrasher, 1996). From 1985 to present, the term Moki has been used in literature to focus on the Middle Miocene submarine fan deposits in Taranaki Basin.

Bussel (1994), studied the Moki Formation in the Maui Field in the southern Taranaki Basin. He described the Moki Formation as sandy turbidite deposits interbedded with claystone produced from a relative sea level fall in the late Langhian stage (15.1 Ma). In Bussel's study, the Moki Formation was subdivided into Sand A and Sand B with claystone in between. The younger Sand A accumulated downslope of the Giant Forest Formation and was channelized extensively whereas Sand B, which was derived

| | |
|---|---|
| Bussel, 1994 | Reservoir characterization in Maui Oil field |
| De Bock, 1994 | Depositional environmnet |
| Dauzacker et al., 1996 | Structural development of anticlines in Mania oil field |
| King & Thrasher, 1996 | Paleogeography and depositional environment |
| Rogers et al, 2000 | Reservoir characterization in Maari oil field |
| Engbers, 2002 | Seismic geomorphology in Maui oi field |
| Grain, 2008 | Paleogeography and depositional environment |

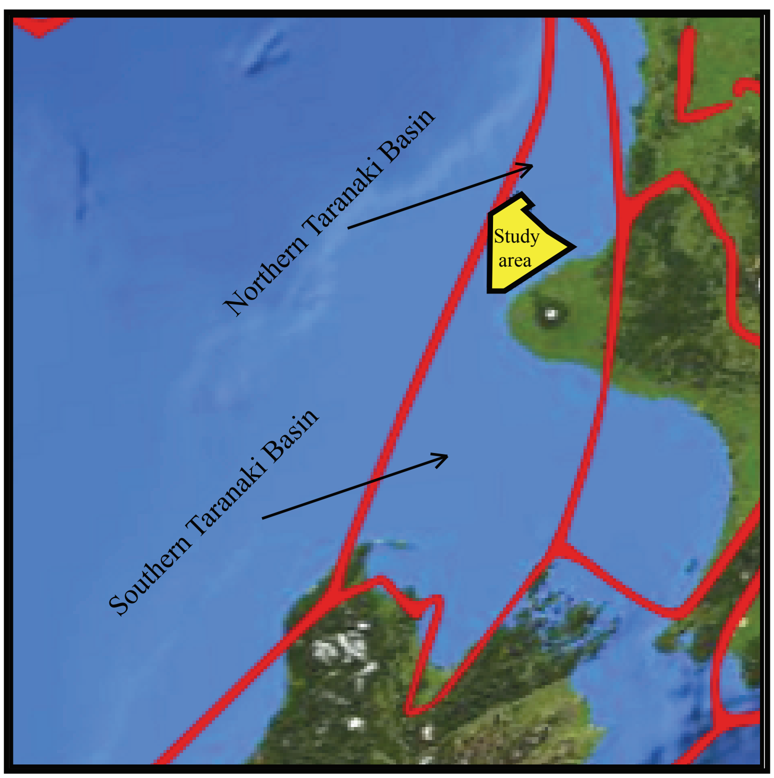



Figure 1.3: The geographic subdivision of the Taranaki Basin and the researches that has done in southern Taranaki Basin. This study investigated the northern Taranaki Basin.

from southeast-oriented shelf-slope break, was deposited in a bathyal environment as a submarine fan. In Maui Field, the gross thickness of Sand B is 275 m. The total thickness of Sand A and B is about 900 m with an estimated depositional rate about 250 m/Myr. Re-interpretation of the Moki sands by Engbers (2002) suggests meandered submarine paleochannels. The Moki B sand is composed of laterally distributed turbidity sandstones.

De Bock (1994) suggested that the Moki Formation was deposited during the Lillburnian stage (nomenclature is according to the New Zealand geologic time scale) in Middle Miocene as a consequence of relative sea level fall. He worked in southern Taranaki Basin and concluded that the sediment source was to the south and transport to the basin floor comprising a longitudinal sand body of submarine fan. Basin on sediment facies analysis, the Moki formation depositional setting is considered “mid fan channel-levee-overbank” and the transport mechanism involved turbidity currents (de Bock, 1994).

King and Thrasher (1996) examined the Taranaki sedimentary basin, including the Moki Formation. In the southern inversion zone, the Moki Formation is well developed with a thickness ranging from 250 to 350 m. They consider the Moki Formation as northeast-dipping dipping submarine fans deposited during the latest Altonian to the Mid Lillburinain. Sandstones, siltstones, mudstones, and limestones comprise the Moki Formation. The major component is sandstone, with a texture characterized as an argillaceous with very-fine to fine sand grains. The Moki fan deposits are readily recognized as different from the underlying and overlying sedimentary rocks because of their high sand content. Hence, in seismic profiles the Moki section appears clearly as a high amplitude reflector.

In order to develop previously discovered fields in submarine-fan deposits, oil and gas companies have conducted new research. These new data enhance knowledge of the Moki Formation, but on a relatively small scale. In the Moki-Mania area, by further seismic data processing and interpretation, researchers reveal more details about structural elements related to basin evolution. Tectonic events, in the area formed anticlines in the Late Miocene (Dauzacker et al, 1996).

In the Maari area, a horizontal well was successfully drilled between two wells. It proved the continuous horizontal distribution of 80 m thickness of the Moki sandstone with three different cycles of sandstone and shale with a general coarsening upward (Rogers et al., 2000).

A relatively recent study by Grain (2008) determined the fan deposits extension of the Moki Formation toward the east, the location of shelf-slope break and the slope in the southern Taranaki Basin. The thickness of the fan deposits is waning toward north and west of the Taranaki Basin. The sediments were transported into the basin floor from the south across an east-west trending shelf. During Lillburnian stage the Cape Egmont Fault, a fault that affected Moki Formation, was a reactivated reverse fault with a downthrown block toward northwest.

# Chapter 2: Geological Background

## 2.1 Tectonic Evolution and Structural Geology

The Taranaki Basin has undergone many tectonic stages from the Cretaceous to the present. The first stage was a rifted margin. In mid-Cretaceous time, the paleo-Pacific margin of Gondwana broke up and led to spreading of the Tasman Sea during the Late Cretaceous and Paleocene (fig. 2.1). This was followed by a passive margin in the early Paleocene and Middle Eocene, which was represented by post-rift thermal subsidence. In mid-Oligocene, the Pacific plate began to subduct eastward beneath the western edge of what is today New Zealand. The last stage of tectonic development is the convergent margin, which continues to the present. In the Early Miocene, regional subsidence was dominant followed by obduction of Cretaceous and Paleogene sediments and then back-arc extension and local volcanism (fig. 2.2). Then during the Neogene, a right lateral dislocation known as the Alpine fault separated the Pacific and Australian plates. At the present time, subduction of the Pacific plate still continues to shape the New Zealand micro continent (Tiem, 2008).

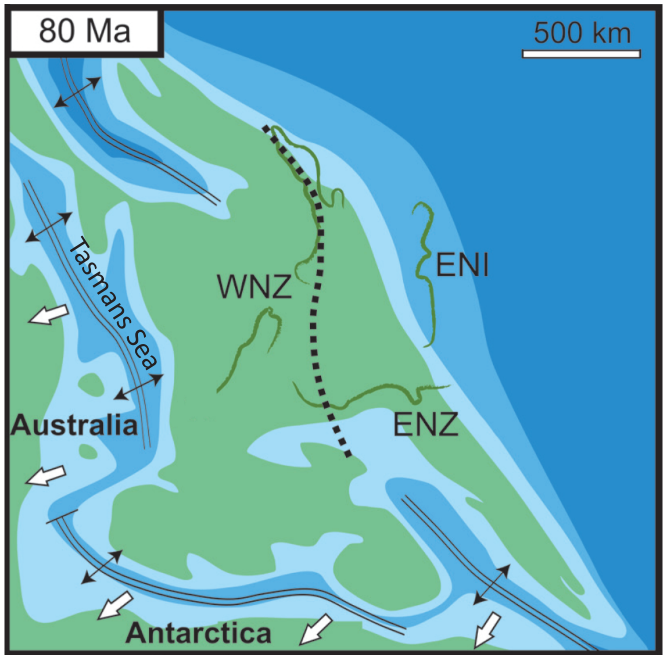



Figure 2.1: Paleogeographic map of the Late Cretaceous shows Gondwana break up, Tasman Sea spreading and the New Zealand microcontinent. WNZ: Western Province, ENI: eastern North Island, ENZ: Eastern Province (after Cox and Sutherland, 2007).

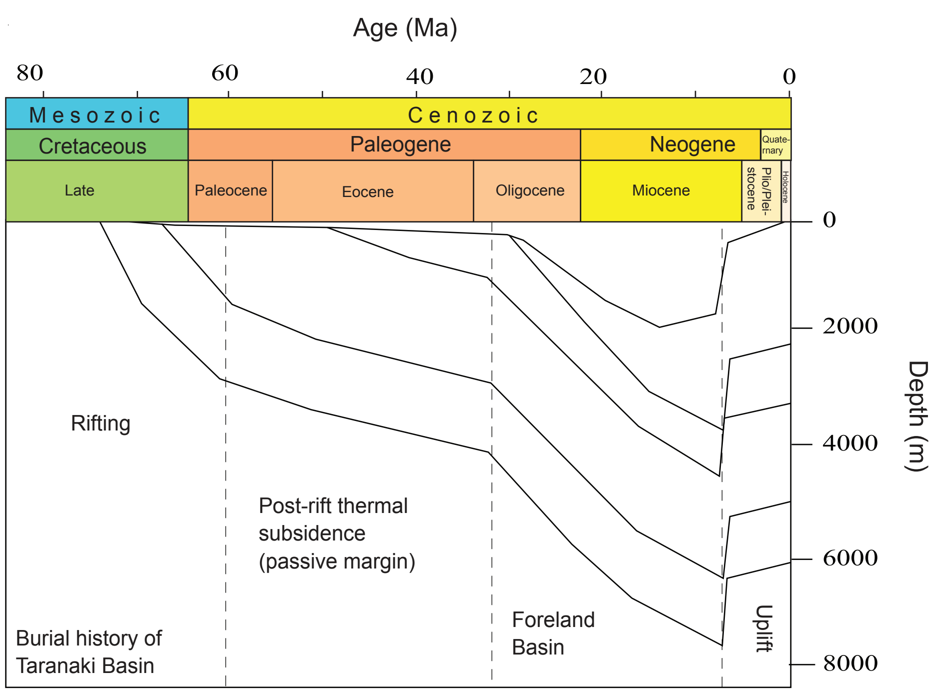



Figure 2.2: Burial history of Taranaki Basin that shows different stages of basin evolution (after Stagpoole et. al., 2002).

### 2.1.1 Cretaceous Rifted Basin

From the Middle Cretaceous to the end of the Late Cretaceous (fig. 2.3), sediments began to infill the newly formed depression formed by half-grabens. This extension was the onset the Gondwana breakup and beginning of Tasman Sea separation at about 80 Ma (King and Thrasher, 1996). The deposited strata now strike NNE-SSW and are mostly of nonmarine origin. Fluvial and deltaic environments were the dominant environments with interpretations of lithofacies as non-marine sand, silt, carbonaceous mud and coal (Tiem, 2008; King and Thrasher, 1996).

The rock constituents of the Upper Cretaceous succession reflect the basement rocks and their structural settings. New Zealands Cretaceous sediments are tectonostratigraphically subdivided into the Western Province, the Median Tectonic Zone, and the Eastern Province (Muir et al, 2000). The Taranaki Basin is situated in the Western Province and the Median Tectonic Zone. The most prominent structural feature within the study area, the Cape Egmont fault zone, separates these provinces. In the Western Province, metasedimentary rocks are remnants of Gondwana. In the Median Tectonic Zone, plutonic rocks are derived from magmatic arcs, with portions of volcanic and metasedimentary rocks as well. The eastern province represents rocks east of the Taranaki fault. They are composed of arc volcanic rocks originally formed along the subducted tectonic margin (Muir et al, 2000).

### 2.1.2 Paleocene-Eocene Passive Margin Basin

After Gondwana break up and initial spreading of the Tasman Sea, the continental margin did not experience significant tectonic activity. The Early Paleocene to the Middle Eocene was a relatively quiescent era in the Taranaki Basin area (fig. 2.4). The Taranaki Basin formed as an intra-continental basin with a wide curved coast facing the deep-sea New Caledonia Basin toward the northwest (King and Thrasher, 1996). During this time, thermal subsidence occurred (Holt and Stern, 1994) within a stable structural setting that became a suitable environment for carbonate deposition (Tiem, 2008; Stagpoole et al, 2002). During the passive margin phase, this proto-continent drifted away from Australian plate toward the southwest. As the drifting phase finished, the Pacific plate began to subduct beneath the New Zealand sub-continent during the mid-Oligocene.

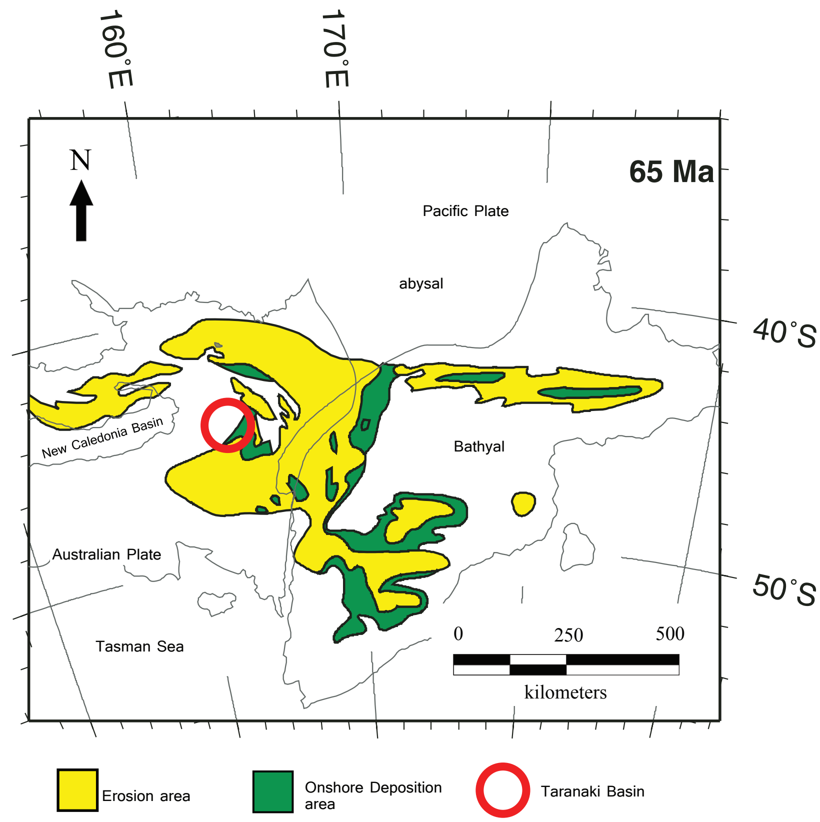



Figure 2.3: Reconstructed paleo-tectonic map of Late Crataceous time (after Wood and Stagpoole, 2007).

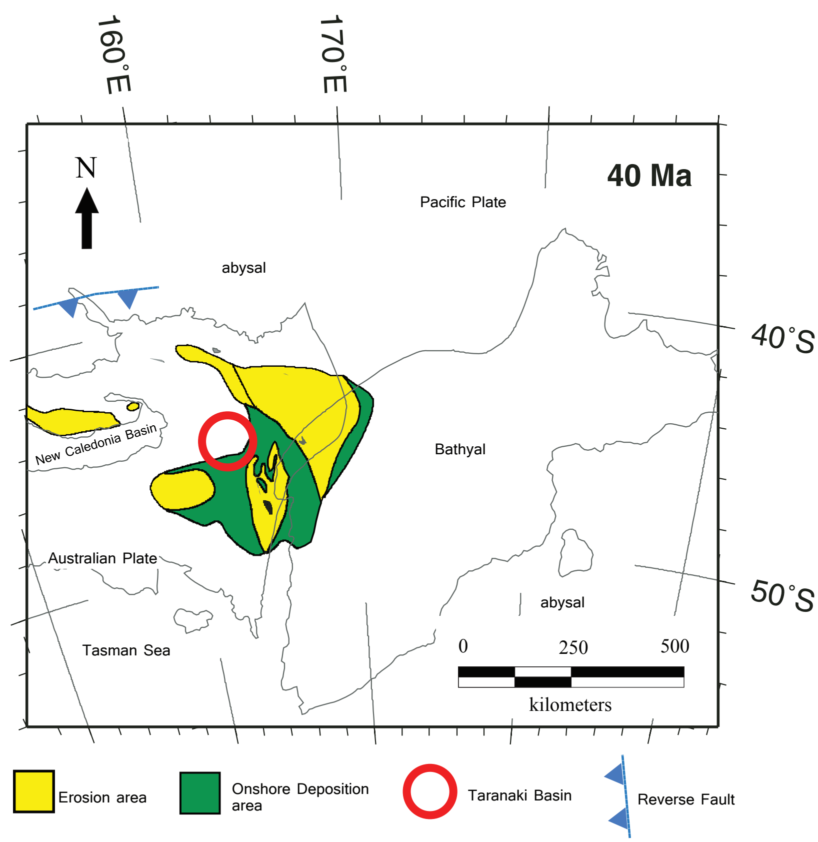



Figure 2.4: Reconstructed paleo-tectonic map of Middle Eocene time (after Wood and Stagpoole, 2007).

### 2.1.3 Oligocene-Miocene Convergent Margin and Retroarc Foreland Basin

The southwest part of the Pacific plate began to subduct beneath westward New Zealand in an oblique direction. Since mid-Oligocene time, this plate boundary has played a major role in shaping the modern configuration of New Zealand. In the Middle Oligocene, the Taranaki normal fault was reactivated as a reverse fault (King and Thrasher, 1996), in response to initial subduction (King and Thrasher, 1996; Holt and Stern, 1994). The Taranaki fault, which forms the eastern boundary of Taranaki Basin, is a thick-skinned fault with high throw of about 4500 m. The intact Pliocene and Pleistocene sedimentary succession indicates the end of Taranaki fault activity in the Late Miocene (Holt and Stern, 1994). New Zealand's proto-continent began to subside as a retroarc basin during Late Oligocene to Miocene time (King and Thrasher, 1996; Holt and Stern, 1994, Stagpoole et al, 2002).

During the Early Miocene, the converging continues and the subsidence became more pronounced (fig. 2.5). At this time, Cretaceous and Paleogene strata was obducted above the western part of the Taranaki Basin, with reactivation of older normal faults as reverse faults. In the south, the Alpine fault was developed along the plate boundary between the Pacific and Australia plates (Tiem, 2008). The Alpine fault marks the plate boundary along New Zealand from the northeast North Island to southwest South Island with a 450 km right-lateral strike-slip motion between opposing blocks (Stagpoole et al., 2002).

### 2.1.4 Late Miocene Back-arc Basin

In the late Miocene, the Taranaki Basin (fig. 2.6) was subjected to tensional stress and become a back-arc basin affected by rising volcanic plumes (Kamp and Furlong, 2006; Tiem, 2008). The age of the Mohakatino Formation, which has a volcaniclastic origin, ranges from10 to 12 Ma. The volcanoes were distributed roughly longitudinally with the youngest to the south in the Taranaki graben (King and Thrasher, 1990). In the latest Miocene, the Cape Egmont Fault Zone was reactivated as a normal fault in response to extension (King and Thrasher, 1990). This fault reactivation resulted in the formation of the North Taranaki Graben.

During the Pliocene and Pleistocene epochs, the graben that formed in the late Miocene propagated toward the south with deposits filling the depression. The Taranaki Graben has a roughly triangular shape with a base toward the north. In the west, the Cape Egmont Fault Zone separates it from the Western Stable Platform, whereas in the east, the Turi Fault Zone forms the basin boundary (King and Thrasher, 1990).

Figure 2.5: Reconstructed paleo-tectonic map of Early Miocene time (after Wood and Stagpoole, 2007).

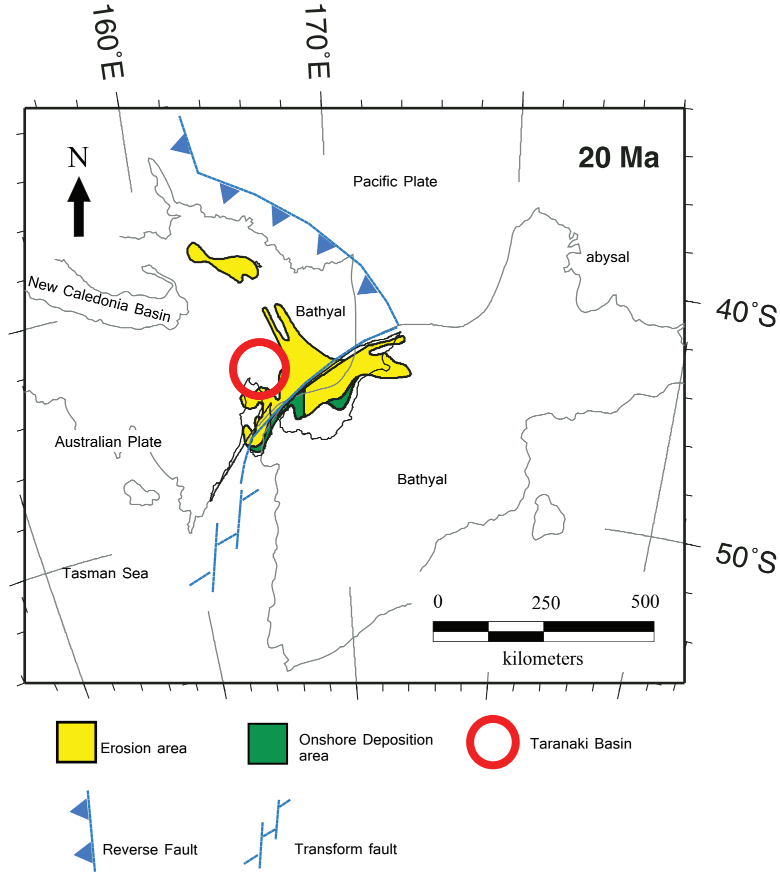
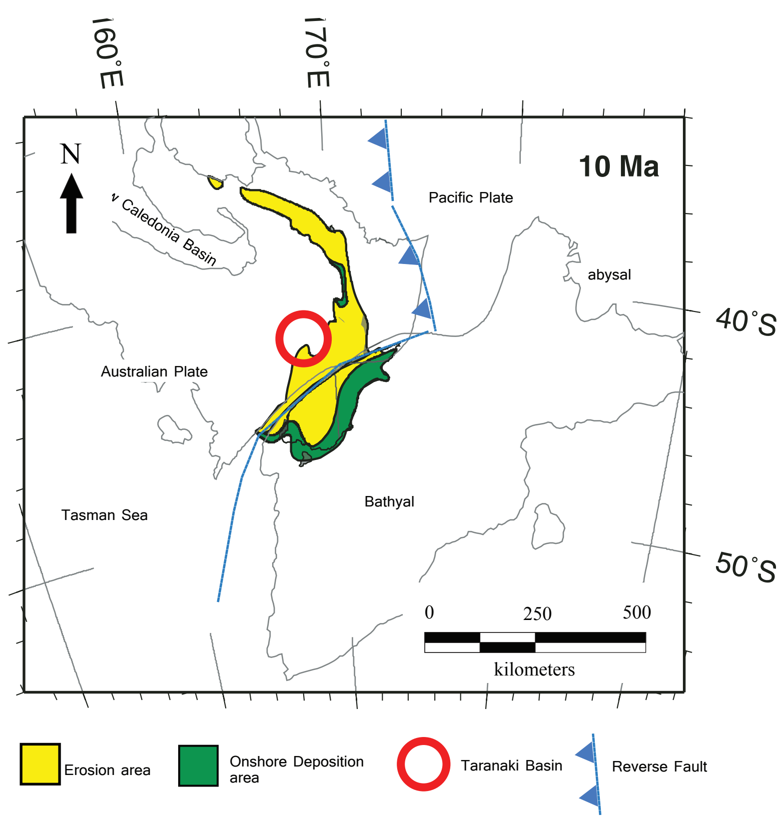



Figure 2.6: Reconstructed paleo-tectonic map of Late Miocene time (after Wood and Stagpoole, 2007).



### 2.1.5 Present-day dominant structures in the Taranaki Basin

Neogene uplift and subsidence (fig. 2.7) was accompanied by high rates of weathering and deposition in provinces that affected by the movement of the plates boundary. The result was a large accumulation of detrital sediments in the recently established basin (Stagpoole et al., 2002) and the overall tectonic and structural setting.

Muir et al. (2000) indicate a close relation between basement structural configuration and basin development. Generally, the sedimentary succession of New Zealand is subdivided into three major areas: Western Province, Median Tectonic zone, and Eastern Province (fig. 2.8). The Cape Egmont Fault Zone separates Western Province and the Median Tectonic Zone and Taranaki Fault zone separates the Median Tectonic Zone and the Eastern Province. The Cape Egmont and Taranaki Fault Zones epitomize principal breakages in the lithosphere and both are oriented north-northeast. The Taranaki Graben represents the area of Median Tectonic Zone (Muir et al, 2000) and the graben itself is subdivided into northern graben and southern graben with a northeast striking Turi fault zone in between (Nooder, 1993).

The Cape Egmont Fault zone in offshore Taranaki Peninsula passes through the middle of the study area. The fault's longitudinal extention is about 200 km with a horizontal range of about 20 km. The fault's history shows many changes in its attitude, with displacement change from normal to reverse and normal again from Late Cretaceous late Pliocene (Nooder, 1993).

Changes in the main effective stress direction along the plate boundary resulted in changes in fault slip. A clockwise stress change and oblique subduction has preserved a tensional tectonic environment in the Northern Taranaki graben (Palmer and Bulte, 1991; Liu and Bird, 2002) and formed the Turi fault zone separating it from the southern compressive Taranaki graben (Nooder, 1993). From the middle Eocene (45 Ma) to present, the effective stress direction changed from north-south to east-west. As a result, the previous normal faults become reactivated as reverse faults (Palmer and Bulte, 1991; Stagpoole and Funnel, 2001; Liu and Bird, 2002).

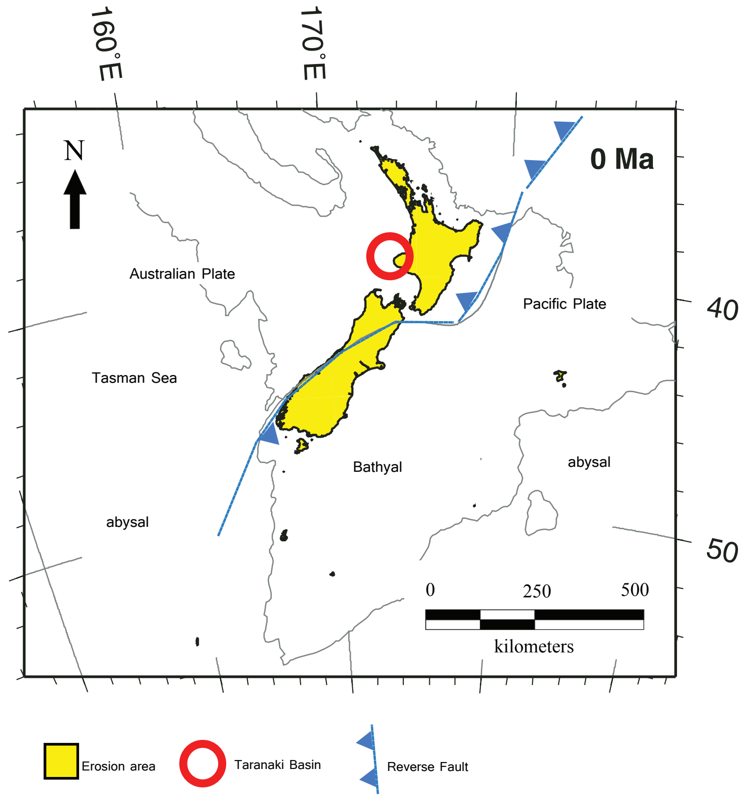



Figure 2.7: Reconstructed tectonic map of present (after Wood and Stagpoole, 2007).

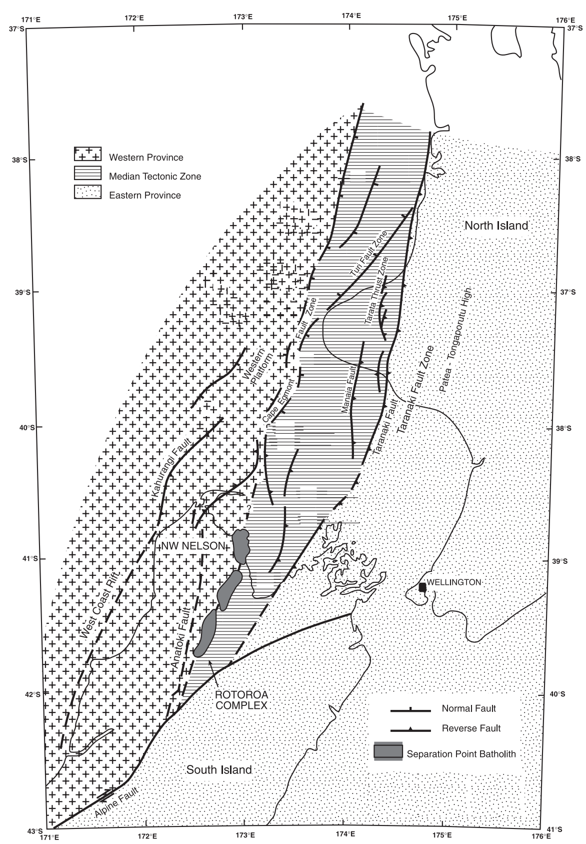



Figure 2.8: Main structural subdivision of the Taranaki Basin, western New Zealand (after Muir et. al., 2000).

## 2.2 STRATIGRAPHY AND SEA LEVEL CHANGE

The multiple tectonics phases that formed the Taranaki Basin have resulted in deposition of a succession about 4-6 km thick. King and Thrasher (1996) subdivided the stratigraphic column into 5 major groups: Pakawau Group, Kapuni and Moa Group, Ngatoro Group, Wai-iti Group, and Rotokare Group. Each group was deposited in a different tectonic environment as follows: syn-rift, post-rift, passive margin, flexural subsidence, and uplift (fig. 2.9).

During the rifting margin phase, which involved break up of Gondwanaland and spreading of the Tasman sea in the mid to Late Cretaceous (Pakawau group) and Paleocene, sedimentation was characterized by shallow marine deposits consisting of coal beds and sands as a result of sea level transgression. During the passive margin phase, the New Zealand subcontinent was in a drift stage and tectonically quiescent. In the early Paleocene (Kapuni and Moa group), the basin experienced post-rift thermal subsidence and marine transgression that led to decreased terrigenous sediment supply and increased carbonate deposition.

In the Middle Oligocene, the Pacific plate began to subduct westward and caused regional subsidence in the Early Miocene (Ngatoro Group). Climate conditions and the restricted landmass helped enhance carbonate growth in the shelf and bathyal environments. From the Middle Miocene (Wai-iti Group), as convergence continued, there was inversion and uplift of land area (Rotokare group) in the southern part of the Taranaki Basin (Tiem, 2008). These activities produced more clastic sediments in coastal plain region.

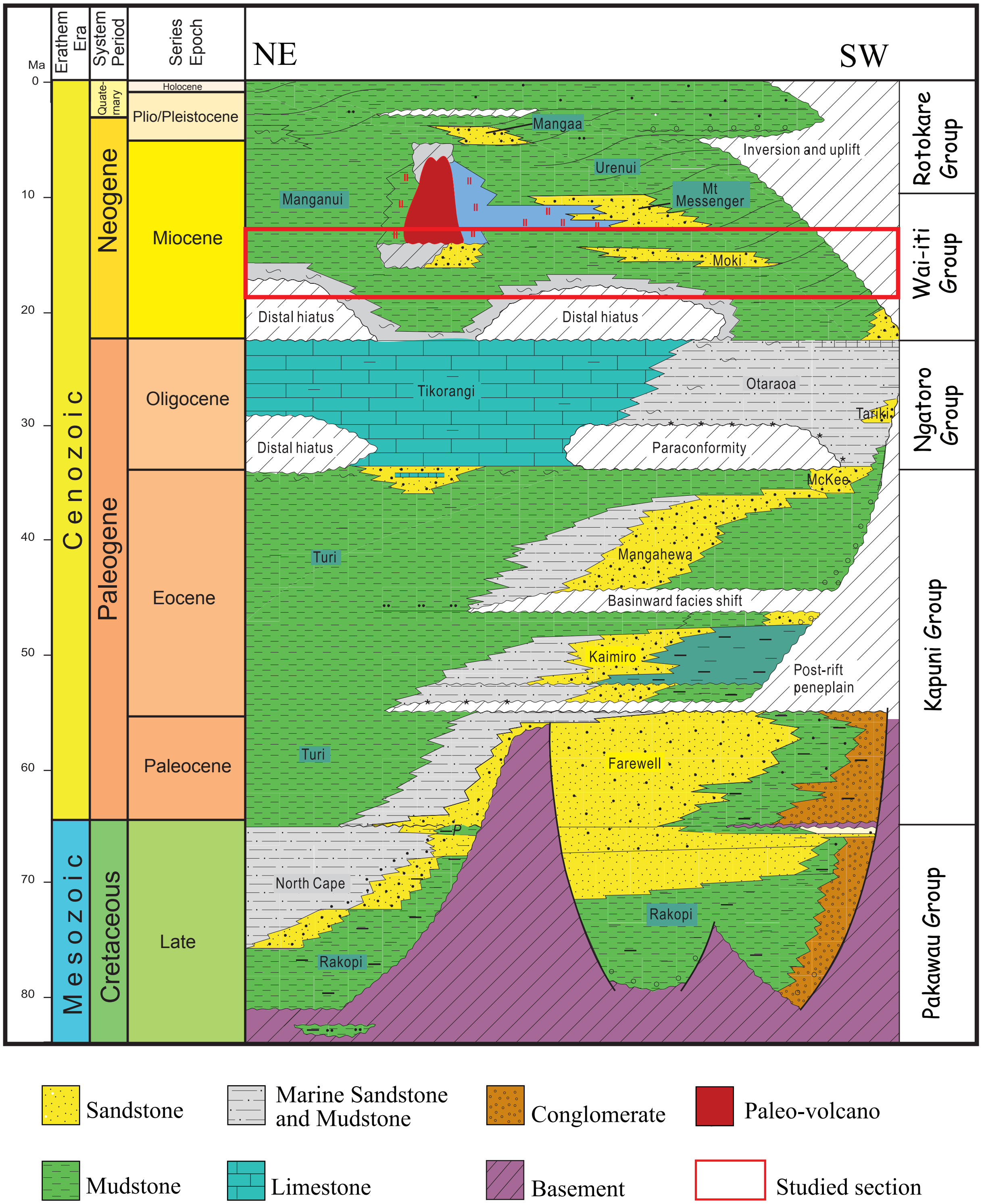



Figure 2.9: Time-stratigraphic chart of the Taranaki Basin with major formations and groups subdivided. The red box includes Moki Formation which is the focus of this study. Modified from the minstry of Economic Development of New Zealand (2010).

### 2.2.1 Cretaceous Pakawau Group

The Pakawau group represents Upper Cretaceous sediments that were related to Gondwana break up. It is composed of non-marine sandstones mixed with conglomerates and mudstones. These sedimentary rocks accumulated after a sea level transgression (King and Thrasher, 1996) and are interpreted as syn-rift deposits.

### 2.2.2 Paleocene-Eocene Kapuni and Moa group

The Kapuni and Moa group is mainly carbonaceous mudstone and coals representing post-rift sedimentation. The age of this group ranges from Paleocene to latest Eocene time. King and Thrasher (1996) interpreted the depositional environment of these sediments as non-marine including fluvial, lacustrine and deltaic environments. The formations included in this group are Farewell, Kaimaro, Mangahewa and McKee Formations. During the Eocene, the sediment pattern changed from non-marine (Kapuni) sediments to Moa Group with calcareous siltstones and sandstones (King and Thrasher, 1996). These fine-grained sediments comprise the Turi Formation, which represents a transgression period in the basin.

### 2.2.3 Oligocene Ngatoro group

From the begining of the Oligocene to the early Miocene, the Taranaki basin did not experience any significant tectonic activity. Formations within the Ngatoro Group consist of mainly carbonates with minimal clastic sediments, including the Otaraoa, Tikorangi, and Taimana Formations (King and Thrasher, 1996). In the Early Miocene, the sea level had reached its highest level leading to a less effective carbonate factory and deposition of argillaceous limestone and marl (de Bock, 1994).

### 2.2.4 Miocene Wai-iti group

The major part of the Miocene sedimentary section belongs to the Wai-iti Group and includes the Manganui, Moki, Mohakatino, Mount Messenger, Urenui and Ariki formations. The Wai-iti Group is characterized by totally marine sediments deposited during an active tectonic phase at a time of regression (King and Thrasher, 1996). The Manganui Formation, which is composed of mudstones and siltstones, has the principal distribution among Miocene units and was deposited on the shelf, slope, and basin floor. The Moki and Mount Messenger Formations are composed of submarine fan sandstones; the other Formations (Urenui, Mohakatino, Ariki) are siltstone, volcaniclastics, and marls, respectively (King and Thrasher, 1996). The Australia-Pacific plate boundary across New Zealand had a major effect during the Miocene. The intensity of convergence increased and the outcome was a high influx of siliciclastic sediments (Hansen and Kamp, 2004) that covered the entire basin.

### 2.2.5 Pliocene-Pleistocene Rotokare group

The most recent deposits within the Taranaki basin stratigraphic column are the Rotokare Group. This grup represents deposits of the Pliocene and Pleistocene including the Matemateaonga, Tangahoe, Mangaa, Gian Foresets formations. These were deposited during sea level regression and uplift of emergent land in the southern region that produced ample sediment supply. The thickness of these Pliocene and Pleistocene Groups range from 2000 to 3000 m and compose coastal to shelf-edge marine environments (King and Thrasher, 1996).

# Chapter 3: Study approach and depositional environment of Moki Formation in the study area

### 3.1 The data utilized

In this study, the available data relate to a 3D seismic volume that covers about 1600 $km^2$ west of the Taranaki Peninsula, with data derived from four wells. Three of the wells were drilled beyond the seismic survey whereas the other one is within the seismic survey.

#### 3.1.1 3D Seismic Volume

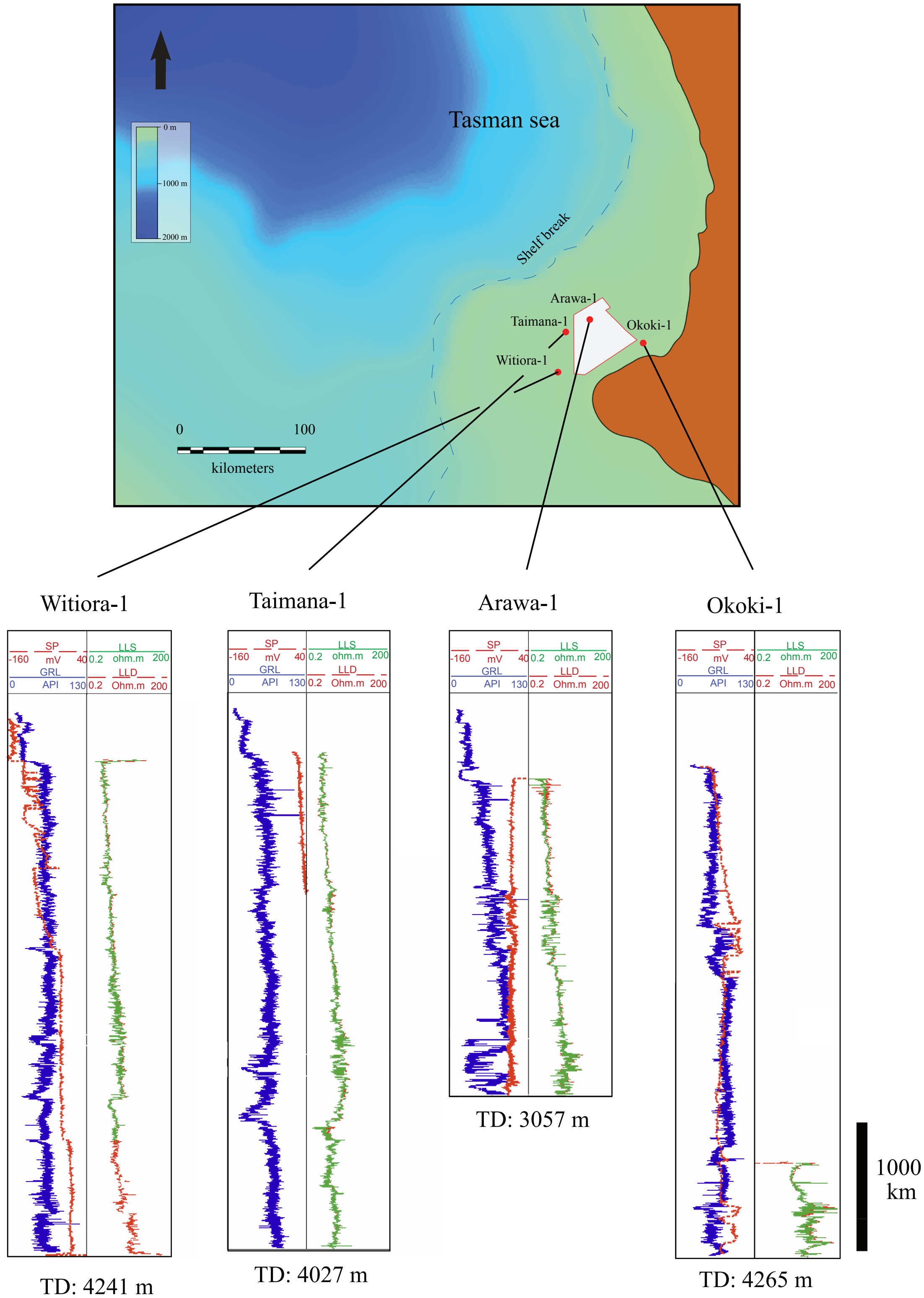
The marine seismic survey covering the study area is known as Parihaka 3D and was completed by Pogo New Zealand. In 2005, the company achieved data acquisition by the crafts Veritas DGC's and Viking II. The Viking II craft was equipped by eight cords, the length of each being 4500 m and separated from each other by 100 m at a depth of 9 m. Four air guns, separated by a distance of 5 m from each other were used for shooting with a pressure of 1950 psi (Cohen et. al., 2006). The seismic volume covers an area of 1600 $km^2$ down to depth of 5000 ms (~ 6500 m). The seismic wavelengths calculated within the top and bottom of the target fan deposits are ~ 90 m with a vertical seismic resolution of ¼ of the wavelength (about 20 m) and an interval velocity of 3200 ms/m. This seismic resolution distinguishes the beds with 20 m thick and larger.

### 3.1.2 Well data

The four wells used in this study are Witiora-1, Taimana-1, Arawa-1, and Okoki-1. The log used in lithologic discrimination and correlation was the gamma ray log. All four wells are offshore in various water depths (but all less than 100 m) and were drilled to different depths (fig. 3.1). For the wells Witiora-1, Taimana-1, Arawa-1, and Okoki-1 the respective depths are 4241 m, 4027 m, 3057 m, and 4265 m. To make the time-depth conversion, I defined a best-fit line (fig. 3.2) with a linear equation from the average velocity and the two-way travel time value for the three wells that contain fan deposits of Moki Formation. The linear equation helped in determining the depth of the Moki Formation, which is about 3000 m.

## 3.2 METHODOLOGY

Determining the targeted stratigraphic section and defining a clear outline for the deposits and their accumulation history was done in several steps. For distinguishing the Moki Formation and defining of the stratigraphic surfaces in the study area, comparison of composite log with seismic profiles helped in well–seismic tie. Software computer programs I used in horizon interpretation and analysis were Landmark suite's Geoprobe, Seisworks and Stratworks and ArcGIS.




Figuer 3.1: Map of the offshore region west of North Island in New Zealand showing the utilized well locations and the availabe logs in each well. SP: Sponteneous Potential, GRL: Gamma Ray Log, LLS: Laterolog Shallow, LLD: Laterolog Deep.

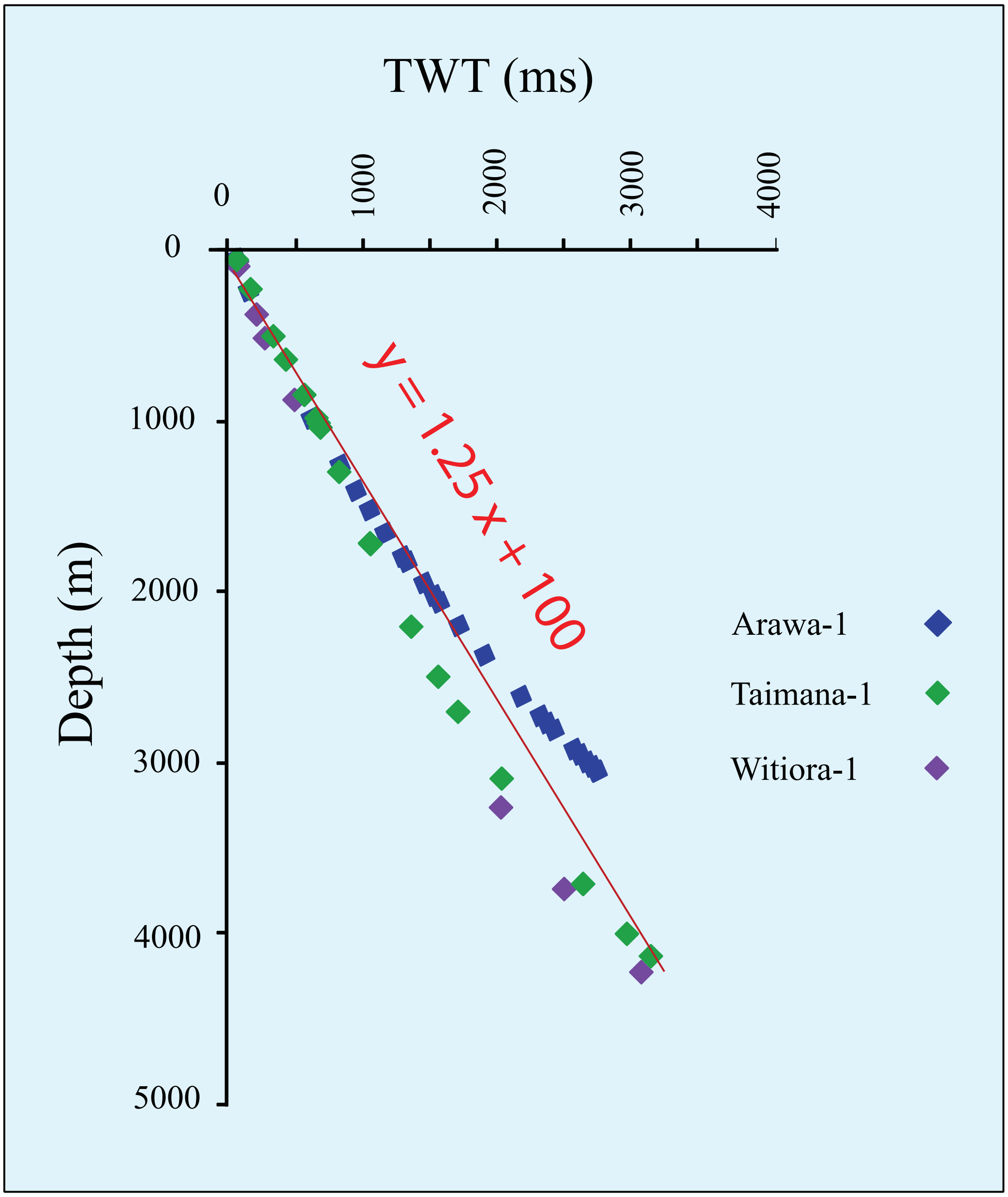


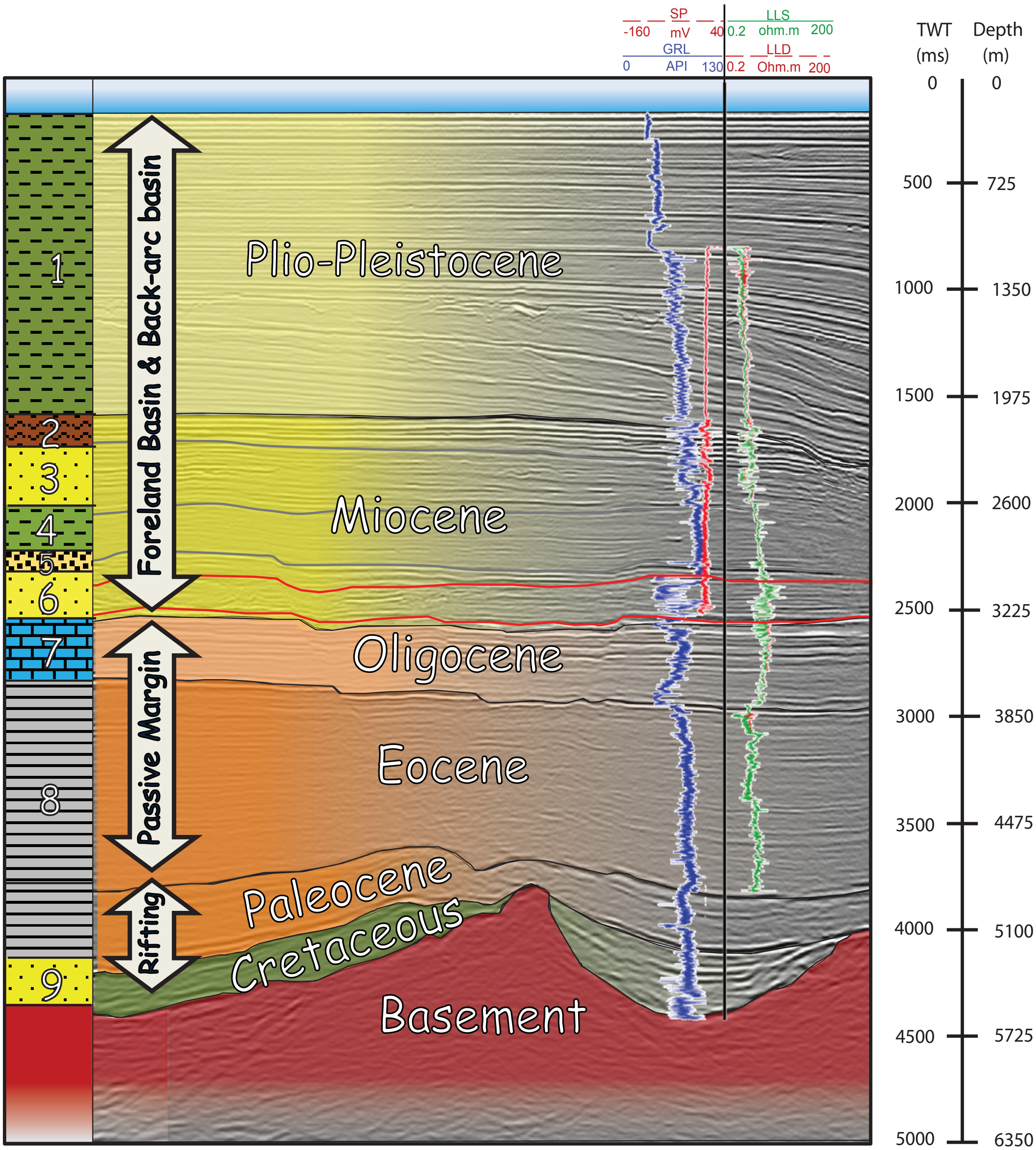

Figure 3.2: The linear equation used in time-depth conversions of reflection seismic data. TWT: Two-Way-Time.

On the seismic sections, five key surfaces could be determined readily based on the amplitude variation of the reflectors. The surfaces are Top Basement, Top Cretaceous, Top Eocene, Top Oligocene, and Top Miocene. Integrating gamma ray logs and published works on the area assisted in defining additional surfaces and formations on the seismic profile and in defining the Moki Formation as submarine fan deposits (fig. 3.3).

Interpretation of the seismic traces and lines for the top and base of the Moki Formation were followed by the key surfaces determination. The Top Moki and Base Moki structural surfaces were generated from the interpreted traces and lines, and became a reference horizon for the following interpretations. After enhancing the Base Moki and Top Moki interpretations, isochron and various amplitude extraction maps were produced. The amplitude extraction maps that gave positive results include windowed and non-windowed amplitude extractions for the Root Mean Squares (RMS), Average Amplitude, and Maximum Positive amplitudes.

Contour maps for the Top and Base of the Moki Formation were also produced to improve the accuracy of the surfaces. Automatically generated contour maps, integrated with the thickness of the Moki Formation in the wells and modified accordingly, led to creation of a composite isopach map for the fan deposits within the study area. To better understand the thickness variation, I conducted a correlation for the available wells and interpretation for the gamma ray behavior in the interested section.

After getting an idea of the general distribution of the fan deposits, searching for




1. Giant Foreset Fn., 2. Ariki Fn., 3. Mangaa Fn., 4. Manganui /Mt.Messenger Fn., 5. Mohakatino Fn., 6. Moki Fn., 7. Tikorangi /Taimana Fn., 8. Turi Fn., 9. Mangahewa /Manui Fn.

Figure 3.3: An interpreted seismic profile shows a composite gamma ray and Two-Way-Time values versus depth values. TWT: Two-Way-Time, SP: Sponteneous Potential, LLS: Laterolog Shallow, LLD: Laterolog Deep, GRL: Gamma Ray Log.

geomorphologic features like paleochannels was the next step. Finally, making stratigraphic (stratal) slices and more amplitude extraction maps provided a clear assimilation about the fan lobe distribution in the offshore Taranaki Peninsula.

### 3.3 NATURE OF SUBMARINE FAN DEPOSITS

Submarine fans are products of turbidity currents that occur along the marine slope and bring sediments from the shelf down to the basin. Shanmugam and Moiola (1988) mentioned that the major factors involved in the processes for submarine fan deposition are turbidity currents and debris flows. Both of these processes are sediments gravity flows that may be initiated by slope steepening, hurricanes, and earthquakes, and lead to sediment transport onto the basin floor (Bouma et. al., 1985). Thinning and fining upward trends are main characteristics that distinguish turbidite beds (fig. 3.4). That is, submarine fans show rapid increases in grain size as they develop above a muddy floor and then a decrease in grain size, as they are the products of turbidity currents.

The submarine fan facies are subdivided into upper, middle, and lower fan, each being different in grain size and lithology variation. According to Shanmugam and Moiola (1988), upward thinning sections that are associated with channels in its base represent the upper and middle fan. Whereas, upward thickening facies represents lower fan (fig. 3.5). Thus, the overall grain size variation of submarine fan deposits from bottom to the top shows thickening and then thinning upward.

The processes of progradation and aggradation lead to the accumulation of the sediments in submarine fan lobes, especially in the case of thick coarsening-upward stacks of sediments hundreds of meters (Shanmugam and Moiola, 1988). The lobe of sediments is primarily the product of progradation. This progradation in addition to aggradation is what produces an overall coursening of grain size and thickening of beds

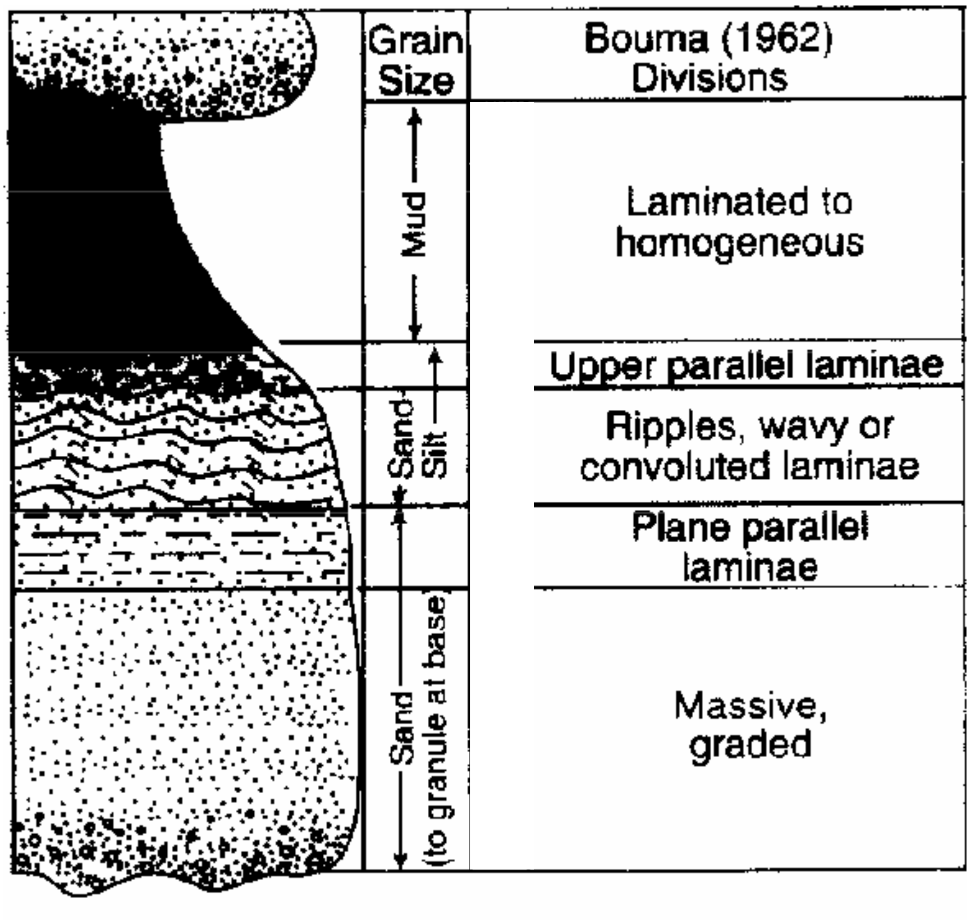



Figure 3.4: Bouma sequence. A typical turbidite facies profile (from Shanmugam, 1997).

(fig.3.6). The sediment supply and the basin floor inclination also control the development of the lobes. Channels that bring sediments from the shelf and slope may undergo avulsion and lead to new lobe formation or incision of the original lobe itself.

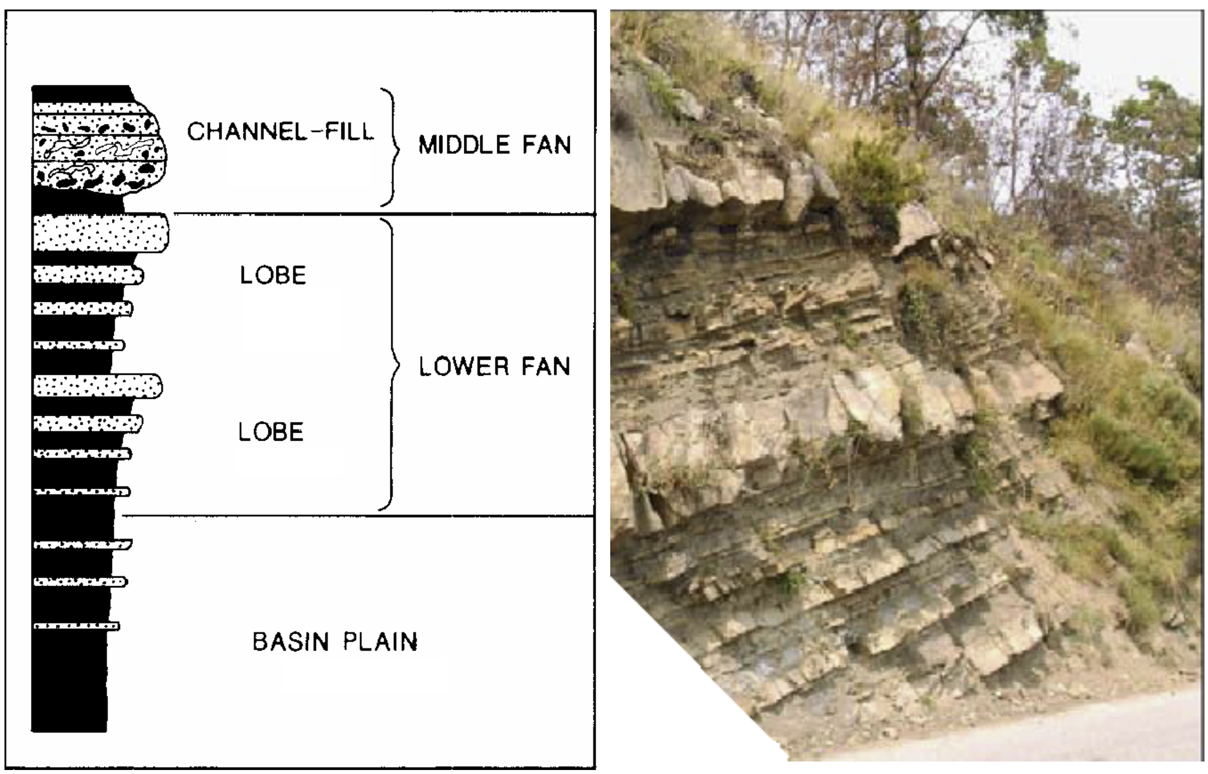



Figure 3.5: Facies model of submarine-fan lobe (after Shanmugam and Moiola, 1988) (left). An outcrop show grain size increasing upward in deposits of a submarine-fan lobe (Veeken, 2007) (right).

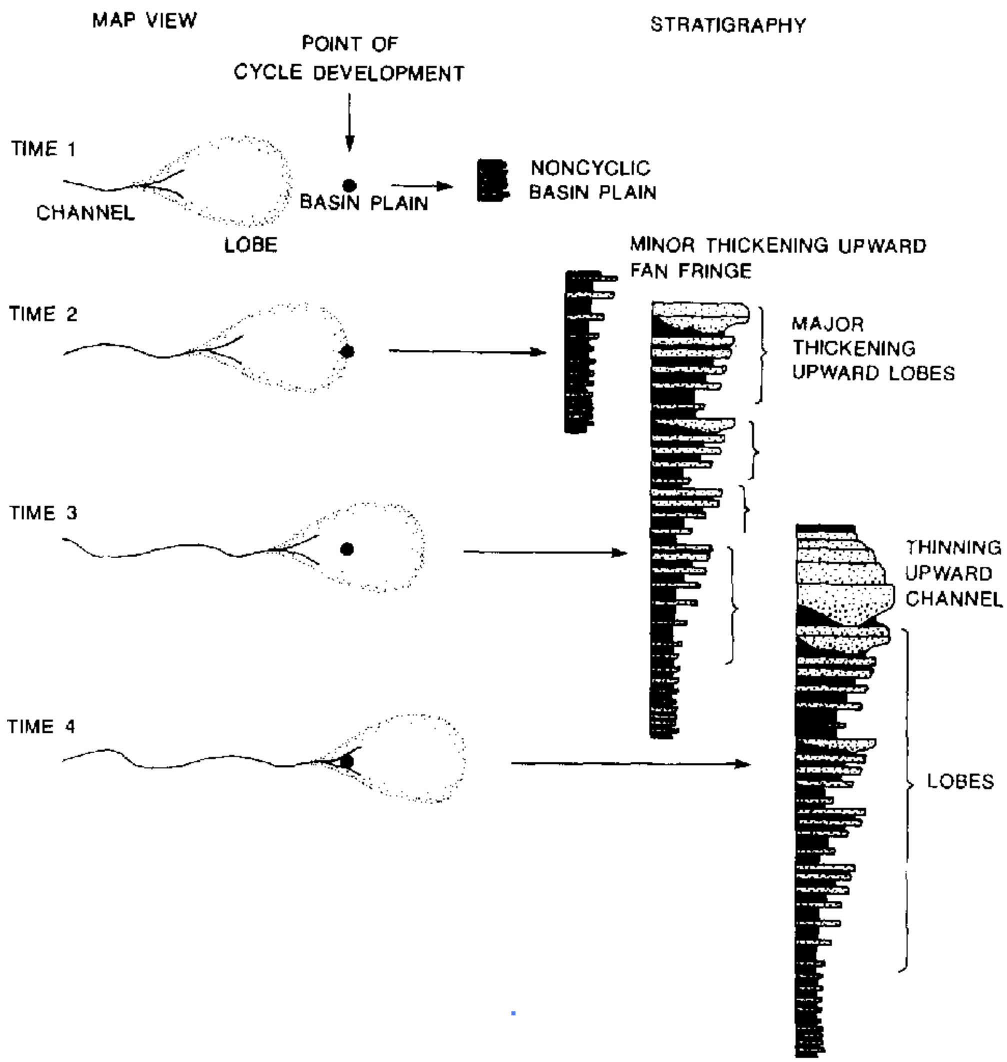



Figure 3.6: Processes of submarine-fan lobe aggaradation and progradation (Shanmugam and Moiola, 1988).

### 3.4 Moki Formation

The Moki Formation is mostly sandy sediment (fig. 3.7) deposited in bathyal environments (Grain, 2008). Jordan (1988) introduced the Moki Formation as fan or inter-fan turbidities (King and Thrasher, 1996) that deposited in the Middle Miocene (17-12 Ma) due to relative sea level fall (fig. 3.8). Sandstones, siltstone, mudstones, and limestone are all components of the Moki Formation, but sandstones are the major component. The grain size is characterized by argillaceous sandstone with very-fine to fine grains (King and Thrasher, 1996). The origin of the sandstone interpreted by petrographic studies, reveals metamorphic rocks of the Separation Point Batholith derived from southern elevated lands (de Bock, 1994). In seismic profiles, chaotic reflections of the Moki fan deposits are situated between continuous reflectors of underlying Oligocene carbonates and overlying hemipelagic muds of the Manganui Formation. Because of the distinctive lithologic difference, with the bounding formations, the Moki Formation is readily recognized in seismic profile.

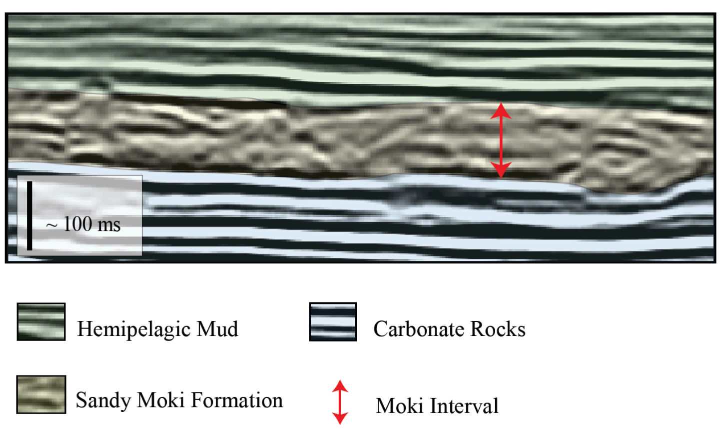
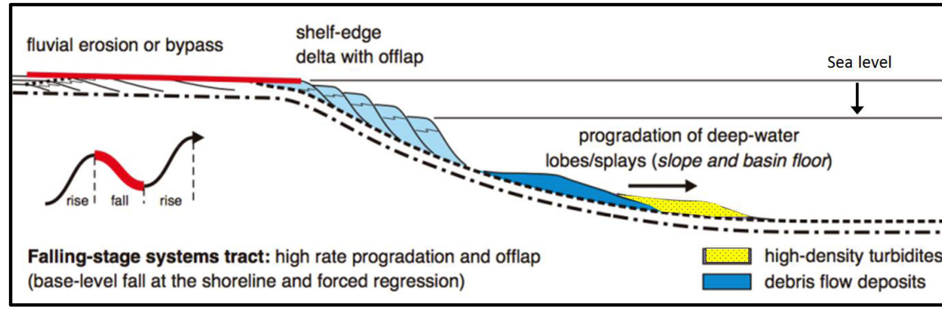



Figure 3.7: Seismic reflectors of Moki Formation between high-amplitude reflectors of carbonate rocks below and hemipelagic mud above.

Figure 3.8: A. Submarine fan deposition due to relative sea level fall (after Catuneanu, 2006). B. Global sea level change from beginning of Miocene to present (after Snedden and Liu, 2010). C. Stratigraphic section shows Middle Miocene Moki Formation (Minstry of Economic Development, New Zealand (2010)

A

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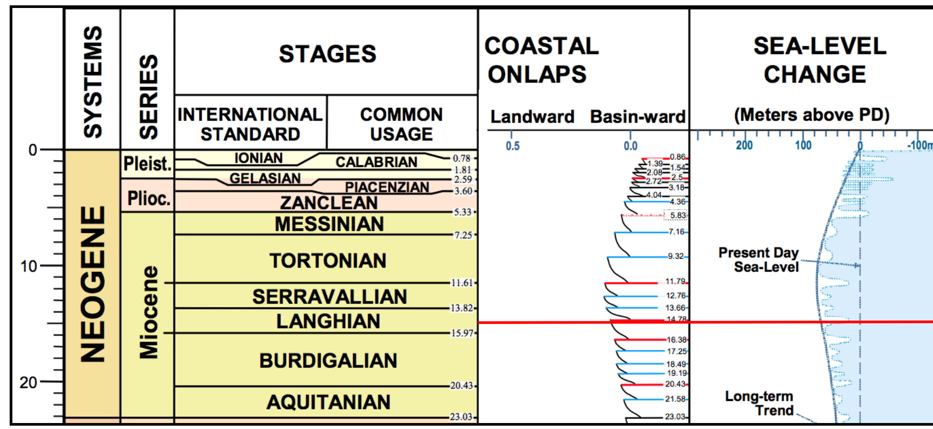


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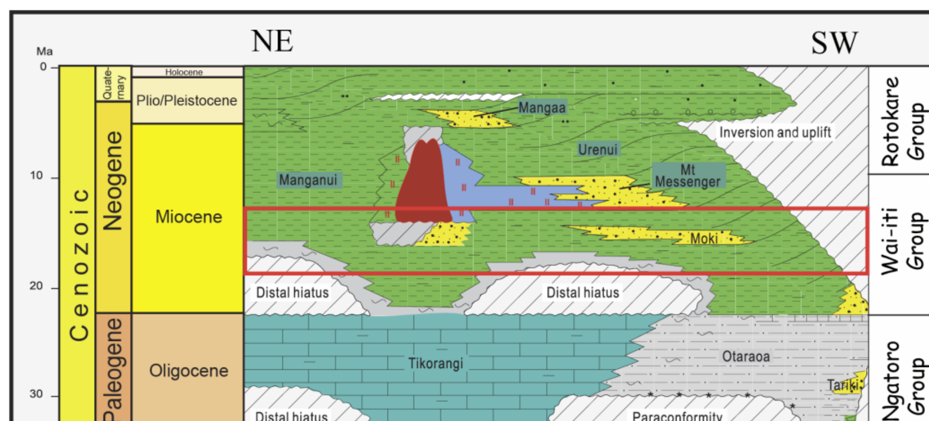


## 3.5 DEPOSITIONAL ENVIRONMENT OF THE MOKI SUBMARINE FAN

The Moki Formation was deposited during the Middle Miocene as a consequence of relative sea level fall. As indicated by King and Robinson (1988), the large sediment supply eroded from uplifted lands in the south due to tectonic activity led to building of the shelf and slope toward the north, depositing submarine fans on the previous stable carbonate shelf.

The targeted fan sediments in the area of this study are stacked, mostly sandy deposits. The well correlation, gamma ray log motif, and seismic profiles and maps promote a clear idea that this ancient submarine fan has the characteristics of the middle fan (according to Shanmugam and Moiola classification, 1988) particularly in the seismically covered area. Incising the lobes by feeder paleochannels and continuous northward progradation and aggradation of the lobes resulted in a thickness of about 300 m in the middle part of the fan complex and less thickness toward the flanks.

Correlations for the wells Witiora-1, Taimana-1, Arawa-1, and Okoki-1 show that the fan does not extend toward the east, because the well Okoki-1 lacks the Moki Formation sandstone in its profile. The well Witiora-1, located in western parts of the study area contains 77 m of Moki submarine fan sediments, including sandstone and shale. This 77m thickness is less than that both preserved in middle Taiman-1 and Arawa-1wells. The thickness increases from west to east in the Taimana-1 and Arawa-1 wells, which are 141 m and 406 m respectively (fig. 3.9).

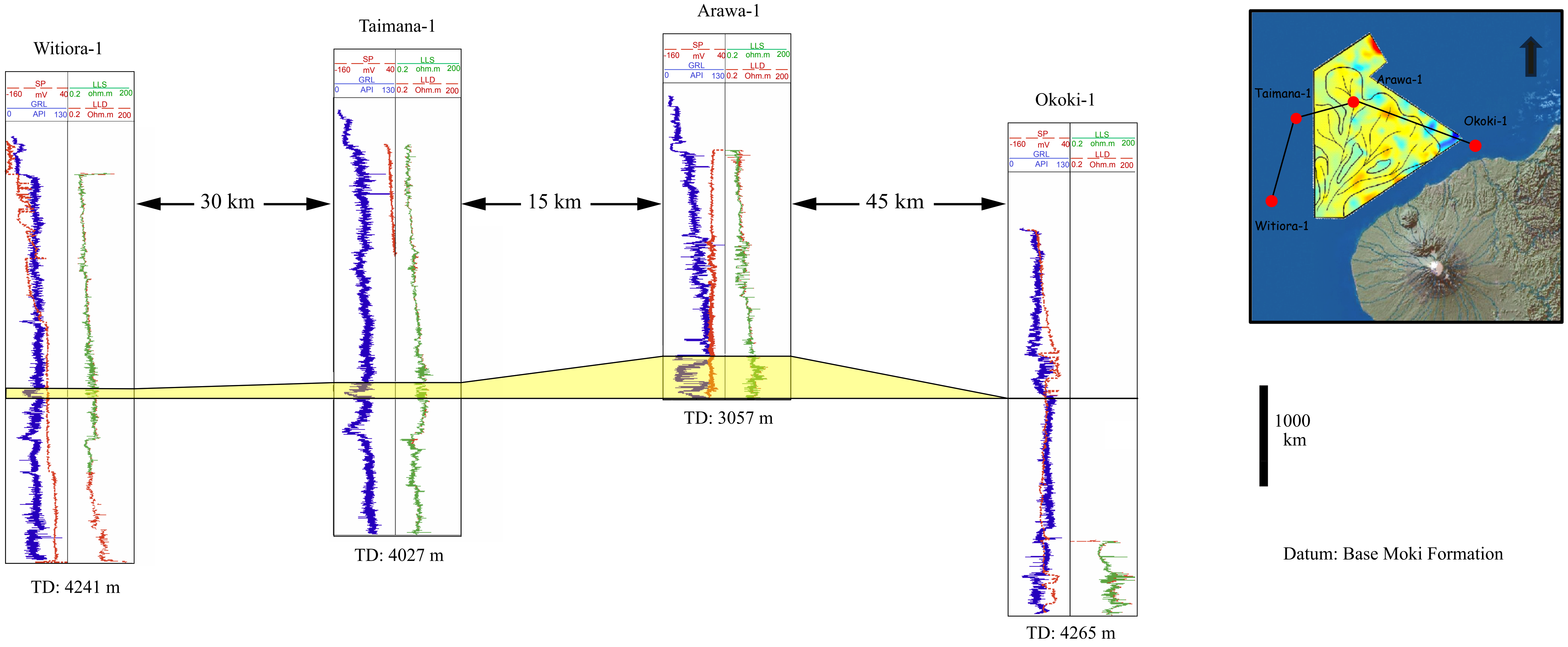



Figure 3.9: Well correlation for the wells Witiora-1, Taimana-1, Arawa-1, and Okoki-1. Highest thickness is in the middle and less thickness toward the flanks. The well Okoki-1 lacks the Moki Formation deposits.

By observing the variation of Moki Formation thickness in the wells, a north-south orientation of progradation is established; the well developed thickness is in the middle, as shown by the well Arawa-1. The absence of sediments within the two wells along the flanks is evidence of the restriction of the fan complex over about ~ 40 km in the east – west direction.

The gamma ray log reflection motif for the stratigraphic section that contain Moki Formation presents a very common submarine fan related motif, especially in the well Arawa-1. Within the three wells Witiora-1, Taimana-1, and Arawa-1 that contain Moki Formation (fig. 3.10), the base of the formation has a sharp base then deflects to the left, indicating increased amounts of sandstone. This sharp change from the shale that belongs to a muddy basin floor epitomizes a clear progradation and dominance of the submarine fan sandstones.

In the well Arawa-1, which shows a 400 m thickness of Moki fan sediments, the stages of fan advancement are very well developed. The log begins with a sharp base then progradation followed by about 200 m of aggradation. The aggradational, continuously stacked fan sediments with more blocky sandstone at the top indicate that the fan was supported by a feeding channel that also incised the fan sediments with a lobe that did not change direction during progradation. The upper part of the gamma ray motif that represents the Moki Formation is characterized by deflection toward the right, indicating increased shale content and change to a muddy deposits. The changes from a sandy to muddy environment is probably because the sandy fan lobe shifted its alignment and the basin floor muds become dominant in the location of the well.

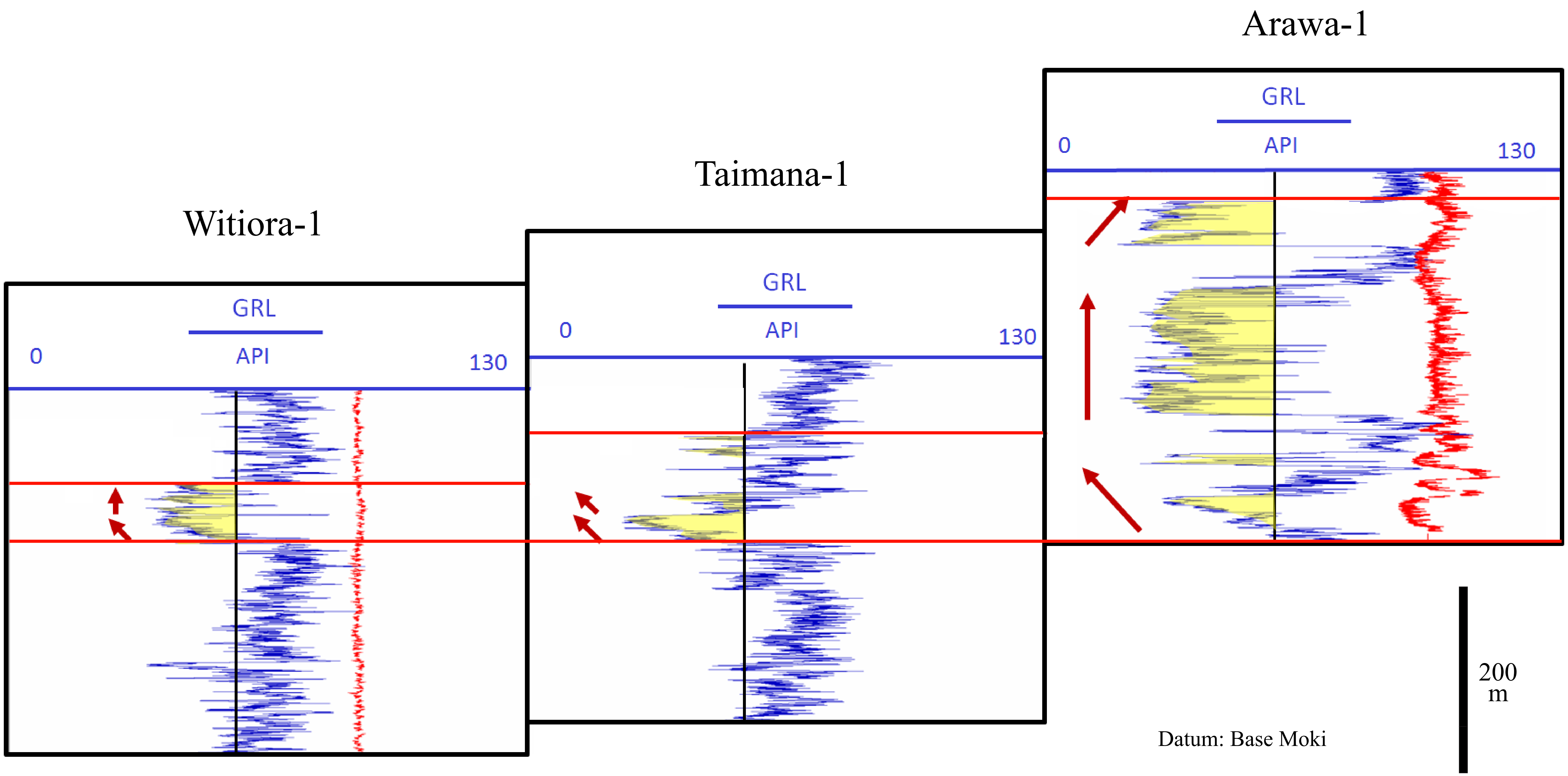



Figure 3.10: Gamma ray reflection behavior of Moki Formation in the wells. In Arawa-1, the fan deposits is well developed and channelized as indicated by the blocky sandstone.

Seismic interpretation of the Moki Formation in cross section and map view verifies the results from well data. A windowed RMS amplitude extraction map between 20 ms below the base and 60 ms above the base of Moki Formation reveal two paleochannels on the western stable platform (fig. 3.11). On the Taranaki graben portion, none of the seismic maps detect any stratigraphic features. Because of the volcanisms that that distributed in Taranaki Graben and numerous faults, the amplitude maps does not show any significant patterns.

Seismic sections across the paleochannels manifest clear evidence for the submarine fan lobes and how were they incised by the paleochanels. Mitchum (1985) published a model that shows seismic reflectors behavior of submarine fans and which described middle fan morphology as a convex-up shape associated with sand-filled channels as the seismic reflectors downlap bidirectionally (fig. 3.12). Shanmugam and Moiola (1988) related Mitchum's bidirectional down lap model to the active margin to describe the submarine fan settings. The seismic reflector configuration of the Moki fan lobes downlap bidirectionally (fig.13) from the depocenter of the lobes to the sides and recognizable paleochannels cut the upper part of the lobes. As stated by profile section of the Moki fan lobes, the tectonically active time of Middle Miocene in the Taranaki Basin can be deduced.

The identified paleochannels are oriented NW-SE and they are within the south-north range of the submarine distribution demonstrated by well correlations. Posamentier (2006) explained that the source of paleochannels could be inferred from acute angle direction of the paleochannels meandering edge. Over time, the sweep that migrates downstream and the swing that stretch laterally produce an indicator of the

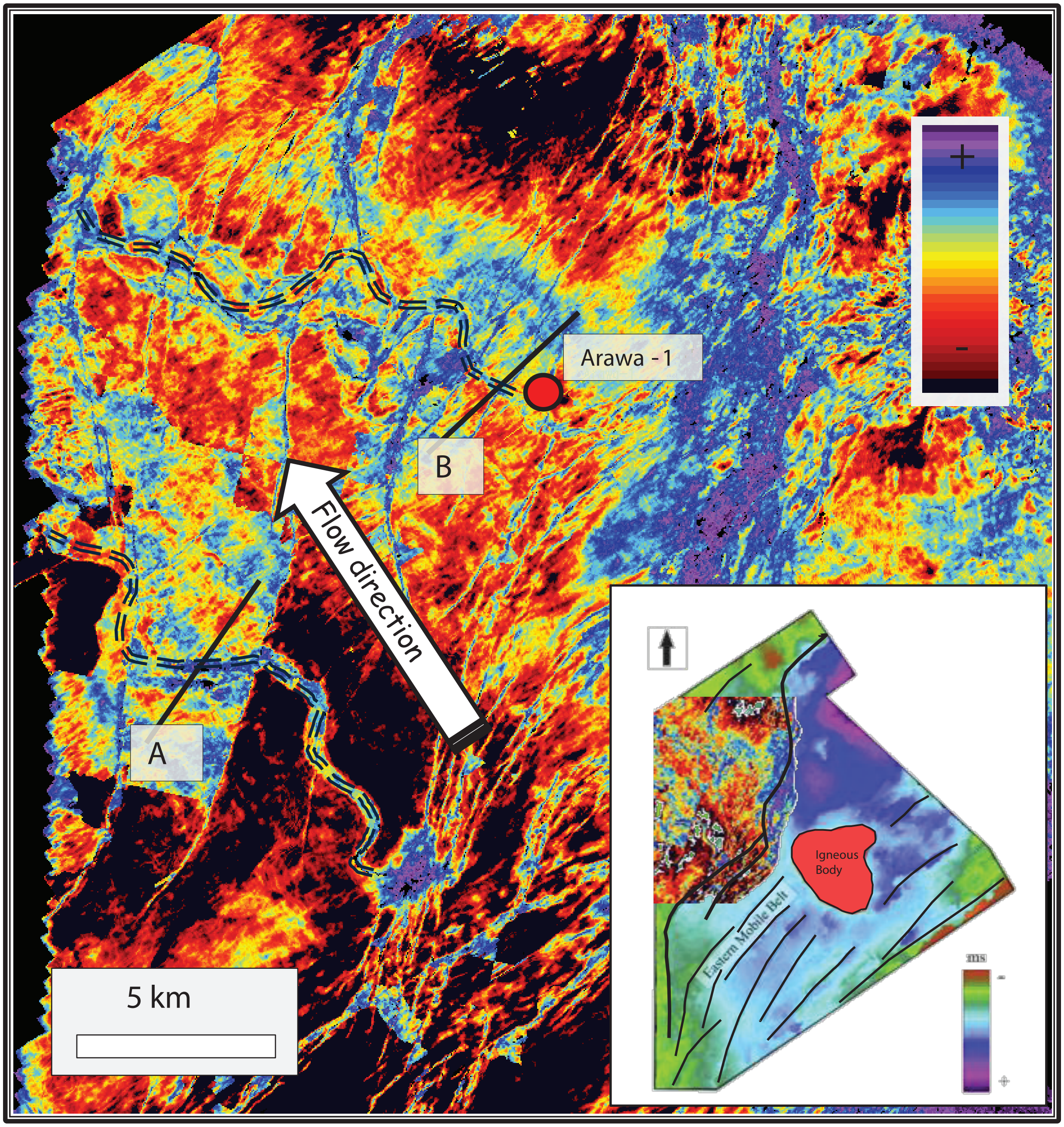
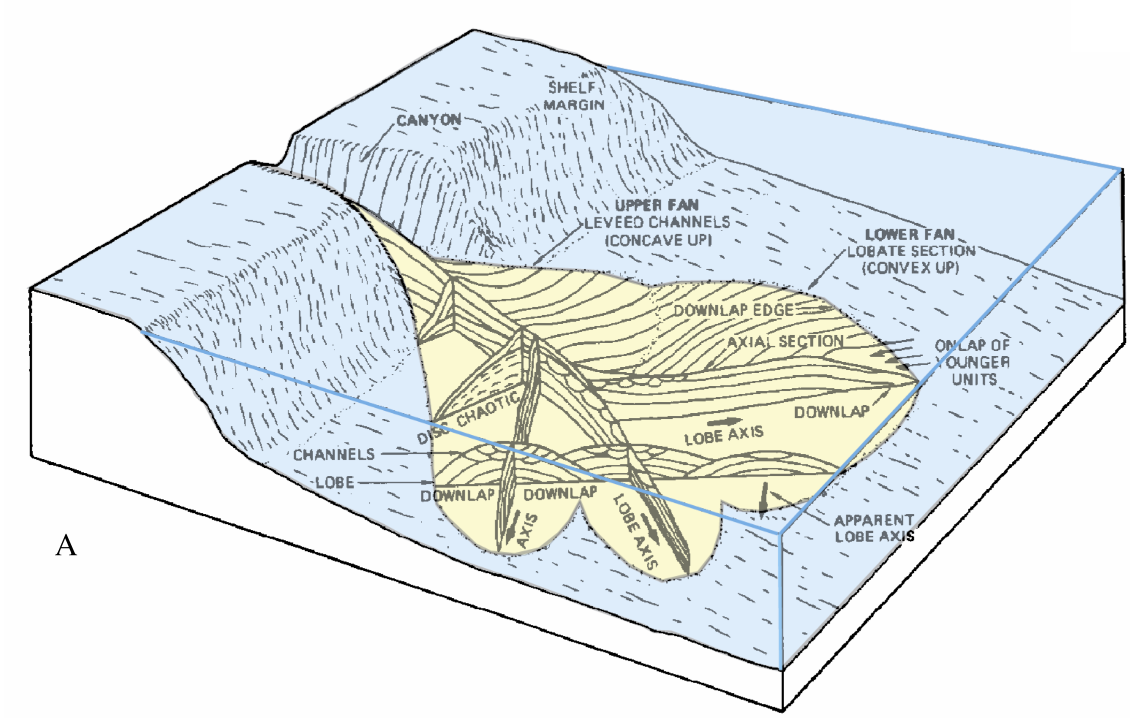



Figure 3.11: Paleochannels detected by RMS amplitude extraction with a window 60 ms above and 20 ms below the base of Moki Formation. The cool and warm colors represent high and low reflectivity respectively. RMS: Root Mean Square. The inset map shows the location of the RMS map on the Base Moki structural surface with. Deep area represented by cool colors.

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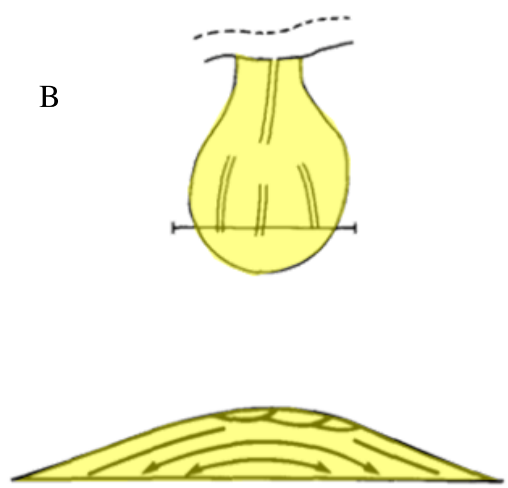


Figure 3.12: A. Seismic reflection models of submarine-fan deposits. (Mitchum, 1985). B. Cross section across the fan lobe shows bidirectional downlap of the reflectors (Mitchum, 1985).

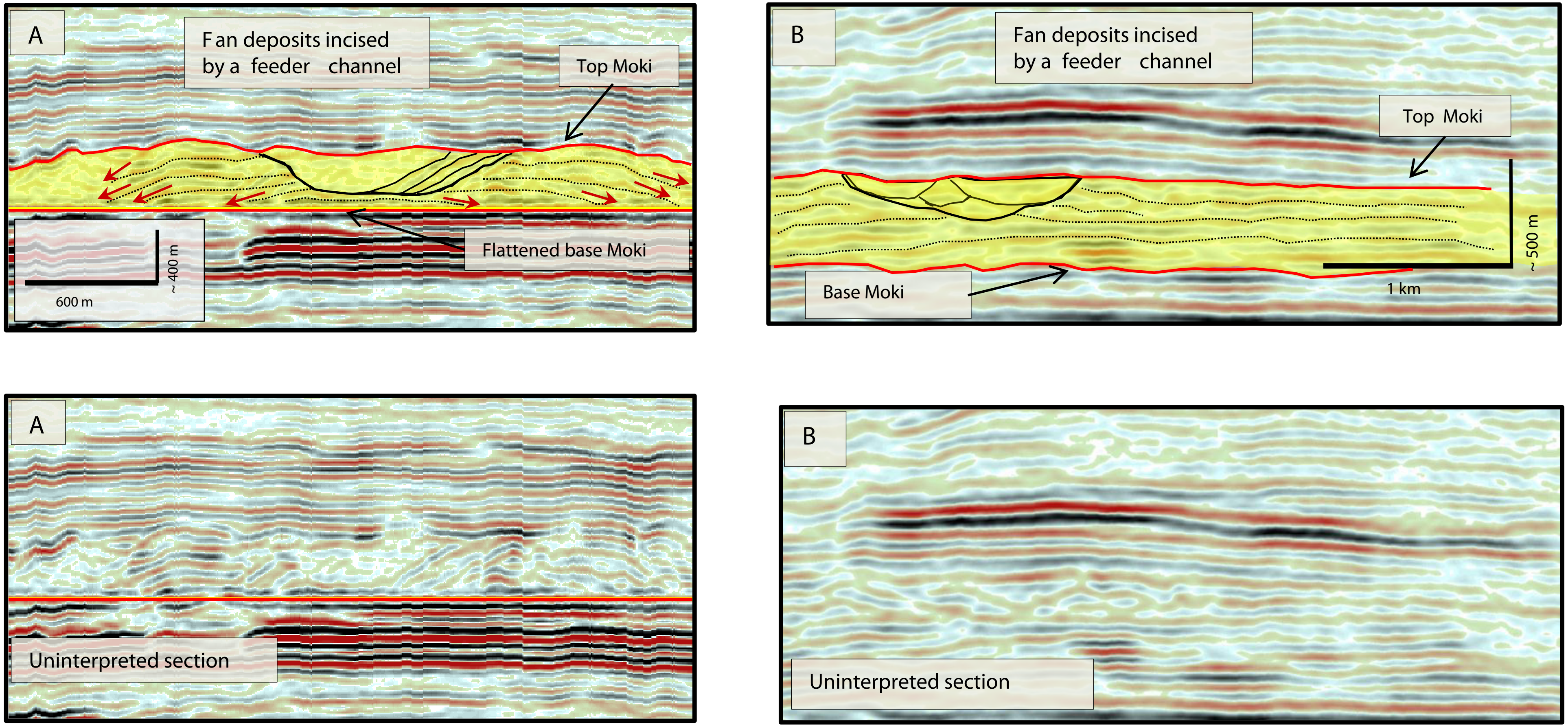



Figure 3.13: Submarine-fan of Moki Formation incised by paleochannels. For the location of the paleochannels see figure 3.11.

flow direction. Accordingly, the two paleochannels of the Moki Formation display a flow direction form SSE to NNW.

Previous studies of the Moki Formation (Grain, 2008; Engbers, 2002; King and Thrasher, 1996; Bussell, 1994; de Bock, 1994) demonstrated the same polarity of the sediment source situated to the south due to the tectonically elevated hinterland in the Middle Miocene.

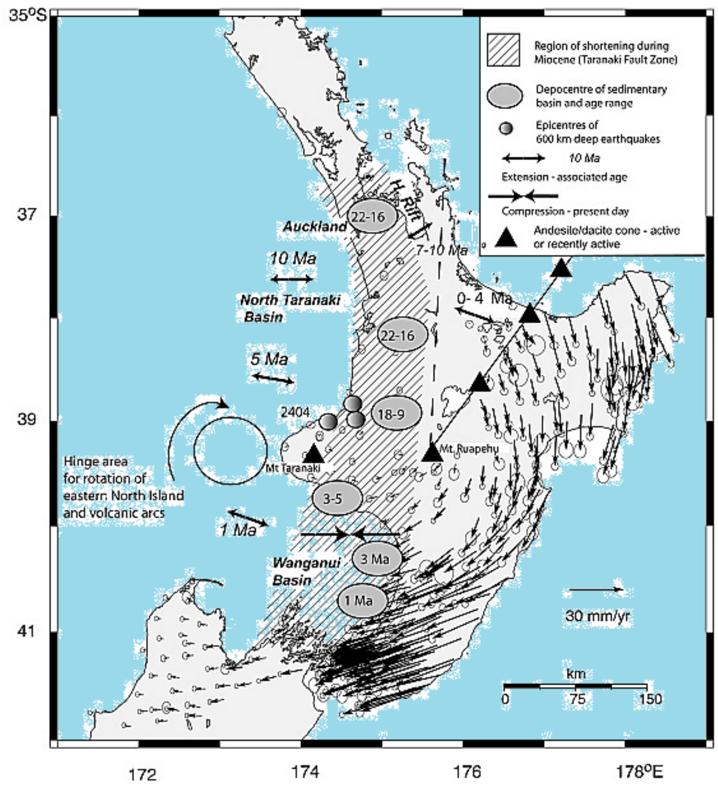
# Chapter 4: Distribution and development of the Moki Formation submarine fans in northern Taranaki Basin

## 4.1 Structural and volcanic effects on the submarine fan deposits

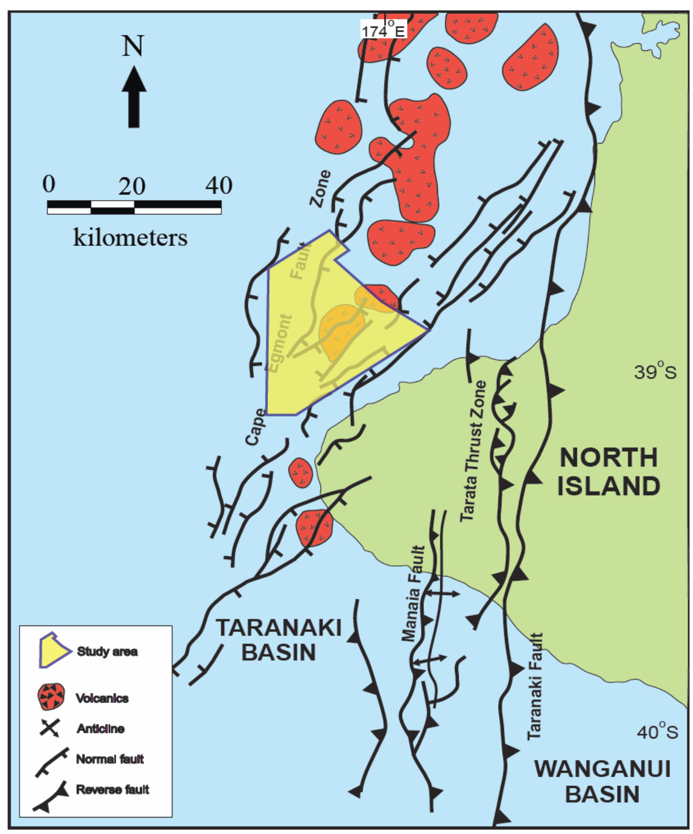
During the Late Miocene, the northern Taranaki Basin experienced tectonic tensional stress due to oblique collision, forming a back-arc extensional basin. The extension and lithospheric thinning induced several rising volcanic arcs. The oldest arc is located in the NE and the youngest in the SW, because of the clockwise extensional opening (fig. 4.1). As a result of the extension in the Late Miocene and previous break up and convergence in the Taranaki Basin, the sedimentary cover, including the Moki Formation, has been deformed considerably.

Interpretation of seismic sections and attribute maps in the study area reflects the geologic history effectively. Within the Parihaka 3D survey, the Cape Egmont Fault is a leading SW-NE growth normal fault with a down-thrown SE. In addition to the Cape Egmont Fault, many other normal faults can be delineated. Beside the fault effects, a paleovolvano exist in the Taranaki Graben (Eastern Mobile Belt) that dated back to the Late Miocene and is located to the east of the Cape Egmont Fault (fig. 4.2). As the age of many faults and the igneous bodies are older than Middle Miocene (the age of Moki Fn.), they do not have syndepostional effects on submarine fan sedimentation. The general uniform thickness of Moki Formation around the igneous body can be noticed readily. In other words, during the time of submarine fan

Figure 4.1: A. Plate tectonic subduction effect on the sub-continent of New Zealand. Opening and extension in the north and shortening in the south along the west of New Zealand (after Stern, et. al., 2006).




B. Distribution of subsurface paleovolcanoes and normal faults as a consequence of tectonic extension (after Crowhurst et. al., 2002).



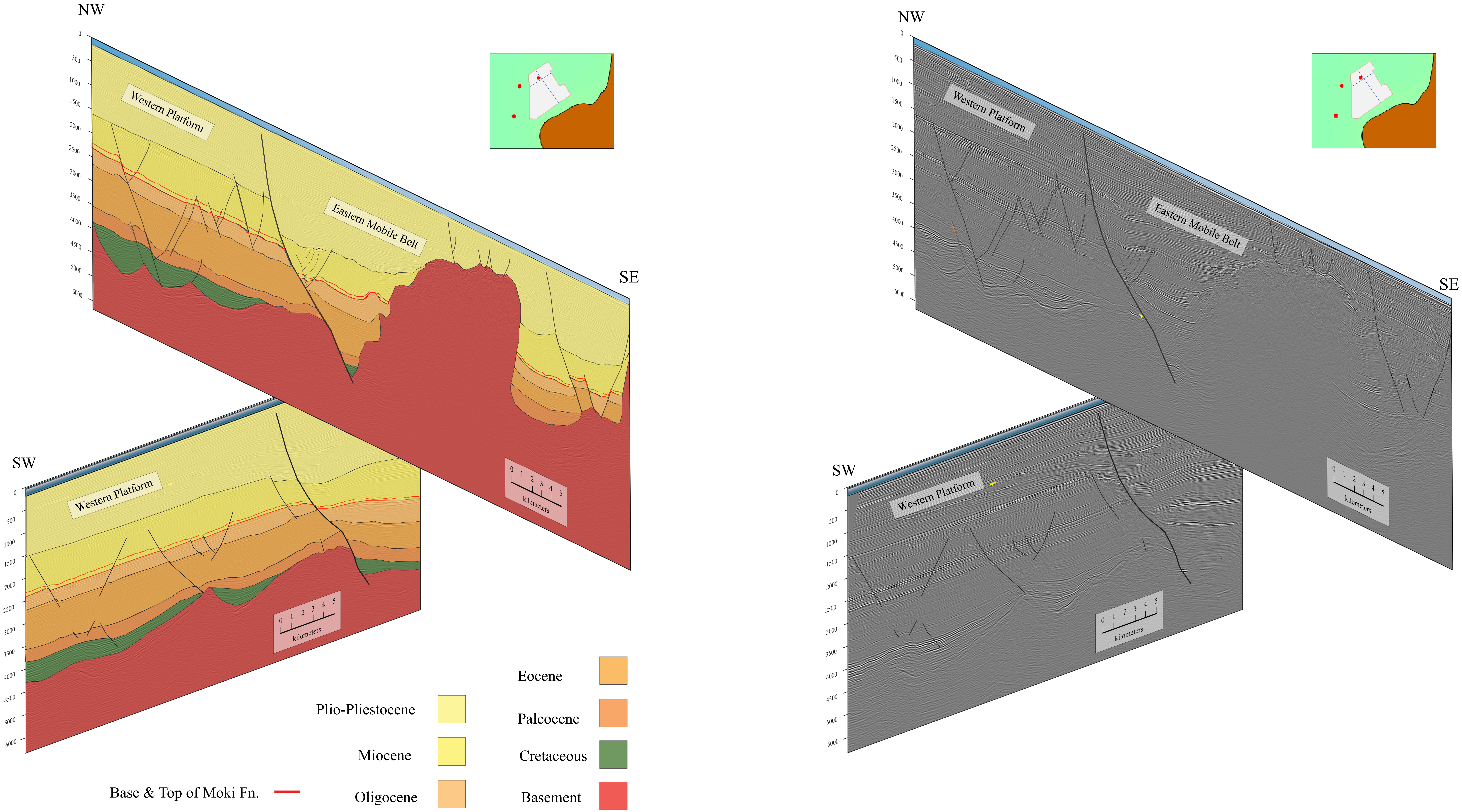



Figure 4.2: Interpreted (left) and Uninterpreted (right) seismic profiles across Parihaka 3D seismic survey. Igneous body and Cape Egmont Fault are two prominent features.

deposition in the Middle Miocene, the basin floor topography had not deformed by faults and there were no structurally controlled depocenters for the sediment accumulation.

Interpretation of the base and the top of Moki Formation highlighted the trace of the faults and volcanisms. An RMS amplitude extraction map of the Moki Formation points out the faults and volcanisms, which also appear on the seismic sections as well (fig. 4.3). Because of the large velocity difference between the igneous rocks and surrounding sedimentary rocks, the igneous rocks show very high amplitude. Fault traces as well are marked by high amplitude appearance. The fault zones probably associated with high pore content that filled by fluids and/or gases. As a result, the wave velocity contrast between surrounding rocks and the fault zones change abruptly and distinct in amplitude map (Corfield et al, 2004).

The structural time-surfaces of the base and top of the Moki Formation (fig. 4.4) exhibit NE-SW faults and volcanic effect that were detected by amplitude maps as well. On the structural time-surface of base of the Moki Formation, the Western Stable Platform, which is the elevated block of the Cape Egmont Fault, is less faulted and less deformed than the Eastern Mobile Belt. The relative intactness of the Moki Formation in the Western Stable Platform helped in detection of stratigraphic features and more accurate mapping than the Eastern Mobile Belt.  In the Eastern Mobile Belt, the downthrown block experienced extensive faulting. In the south and southwestern part of the study area, a full graben had developed within the major half graben. The structural time-surface of the Moki Formation top has the same general configuration and same fault pattern of the Moki Formation base.

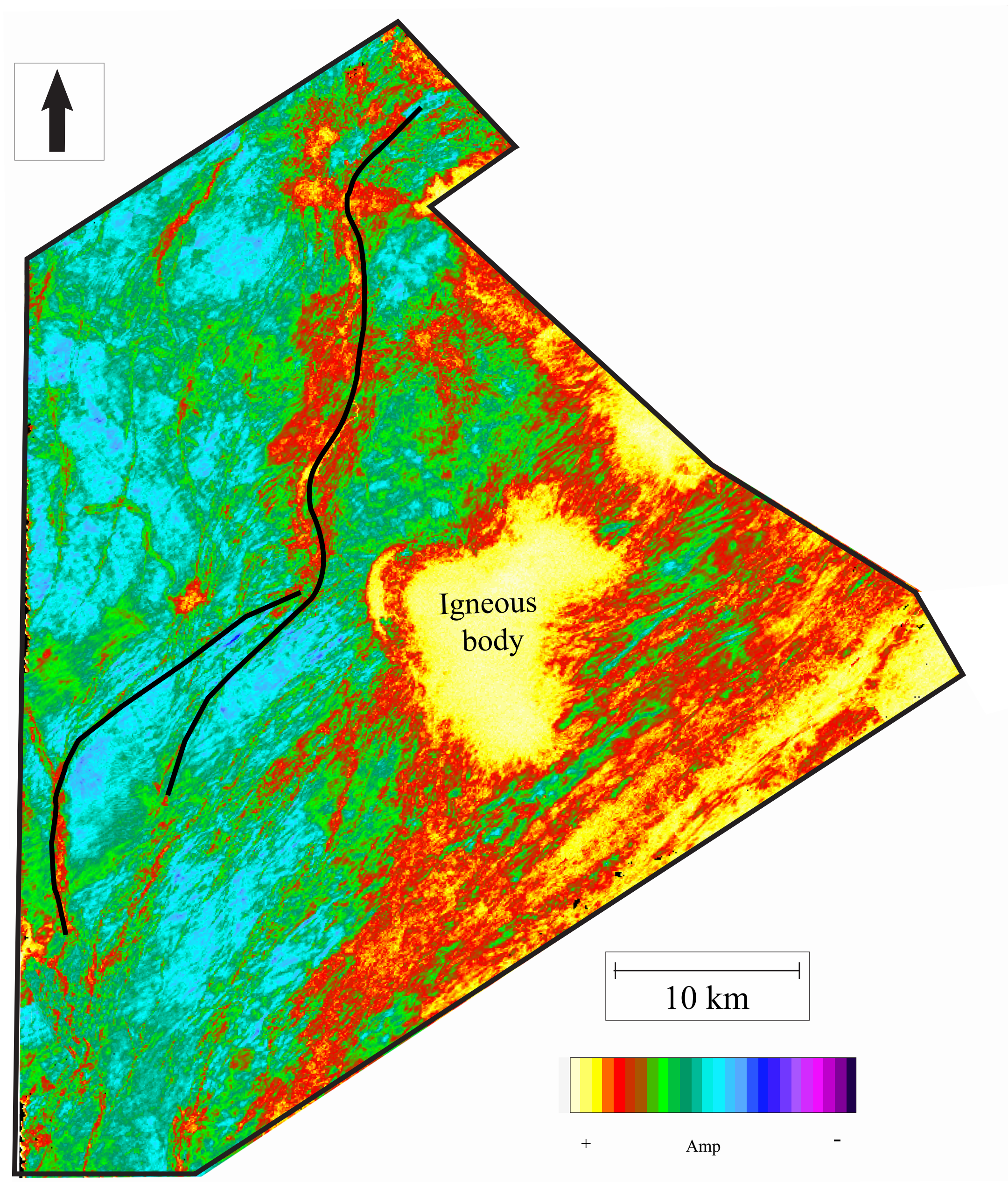



Figure 4.3: RMS amplitude extraction map for 200 ms above the bose of Moki Formation. Volcanic effects and faults represents by high amplitude.

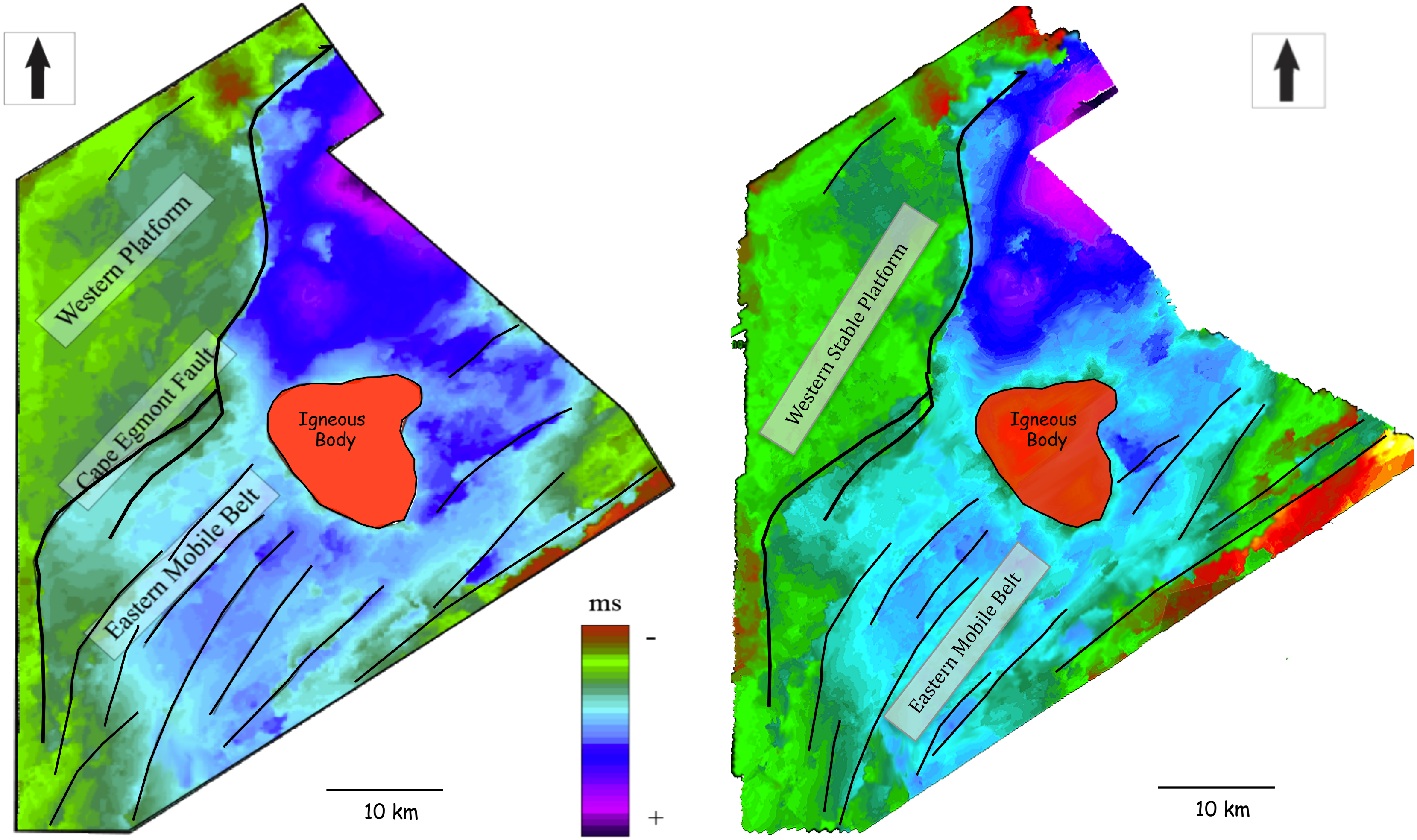



Figure 4.4: A. Structural time-surface of base of the Moki Formation. B. Structural time-surface of top of the Moki Formation.

## 4.2 SUBMARINE-FAN DEPOSITS DISTRIBUTION IN THE NORTHERN TARANAKI BASIN

Interpretations of the well data provide insight into the general orientation and thickness variations of sandstone deposits in the study area. In order to constrain discrepancies in the spatial distribution of the deposits in much detail, seismic interpretation of the Moki Formation provids crucial results and clear visualization about the sediment distribution and alignment of major sand bodies.

Interpretation of the Moki Formation isochron map indicated a general direction of the major sand bodies sourced from the south. The delineated pattern of higher-thickness spots relative to the background thickness gives an overall analogy of submarine fan deposits (fig. 4.5). Because the detected thickness variations from seismic data do not show details clearly, contouring of the base and top of the Moki Formation was a satisfactory alternative. I converted the isochron contour maps to isopach by using an interval velocity of 3200 m/sec. Then, I compared the Moki Formation thickness in the wells with the sand thickness in the isopach map to obtain a more precise isopach estimate. In the resulting map, submarine fan sediments stand out noticeably, with a thickening trend from south to north with lateral dispersion (fig. 4.6). Because the contour maps originated from the structural time-surfaces of the Western Stable Platform, the part mapped with the most confidence, the fan lobes in the northwestern part are well recognized.

In order to extricate a more precise submarine-fan map from the seismic data, I created multiple amplitude extraction maps for the base and top of the Moki Formation

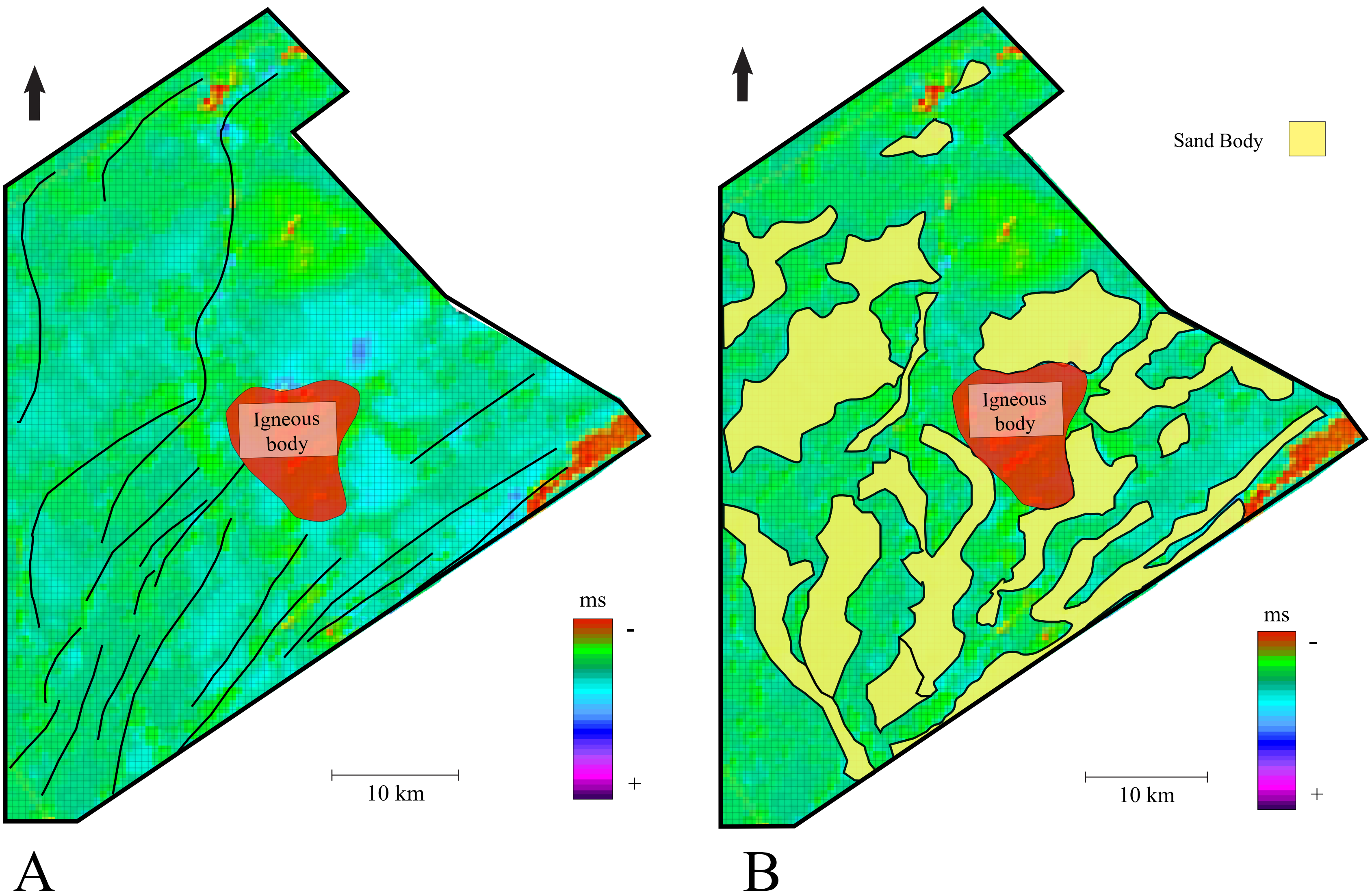



Figure 4.5: A. Isochron map of the Moki Formation. B. Proposed sand bodies distribution as delineation of relatively large thicknessareas suggested

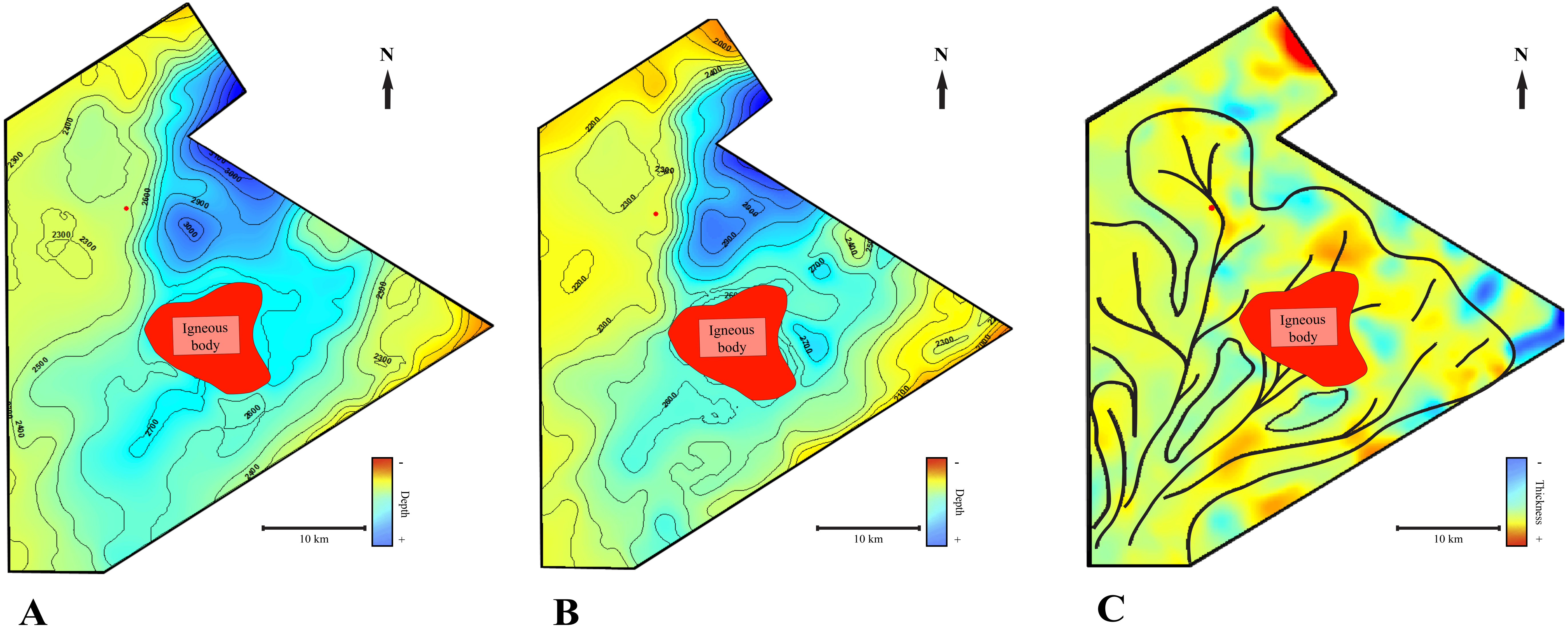



Figure 4.6: A. Contour map of base of the Moki Formation. B. Contour map of the Top Mioki Formation. C. Interpreted submarine fan deposits on the isopach map of Moki Formation that produced from the contour maps of base and top of the Moki Formation.

and also windowed amplitude extraction maps. One of the best seismic images resulted from a windowed amplitude extraction map for the whole range of the Moki Formation (fig. 4.7). The map is windowed from the base of the submarine fan deposits to 90 ms above the base.

Depending on the amplitude variation, several fan lobes were outlined and the interpretation conducted with sufficient confidence as the output submarine fans features extracted directly from seismic data. The high amplitude patches in the map represent the greater thicknesses of the submarine fan deposits. The defined deposits correspond well to the previous submarine fan maps that had been produced from the isochron and isopach maps as shown in figures 4.5 and 4.6.

In brief, the interpreted seismic maps confirm the interpretation suggested by the well data. All the interpreted maps show submarine fan deposits sourced from the south, as can be inferred from a narrow distribution in the south and wider distribution in the northern area. Within the submarine fan complex, several fan lobes discriminated with distinctive boundary according to large thickness pattern distribution of the lobes according to the surrounding deposits.

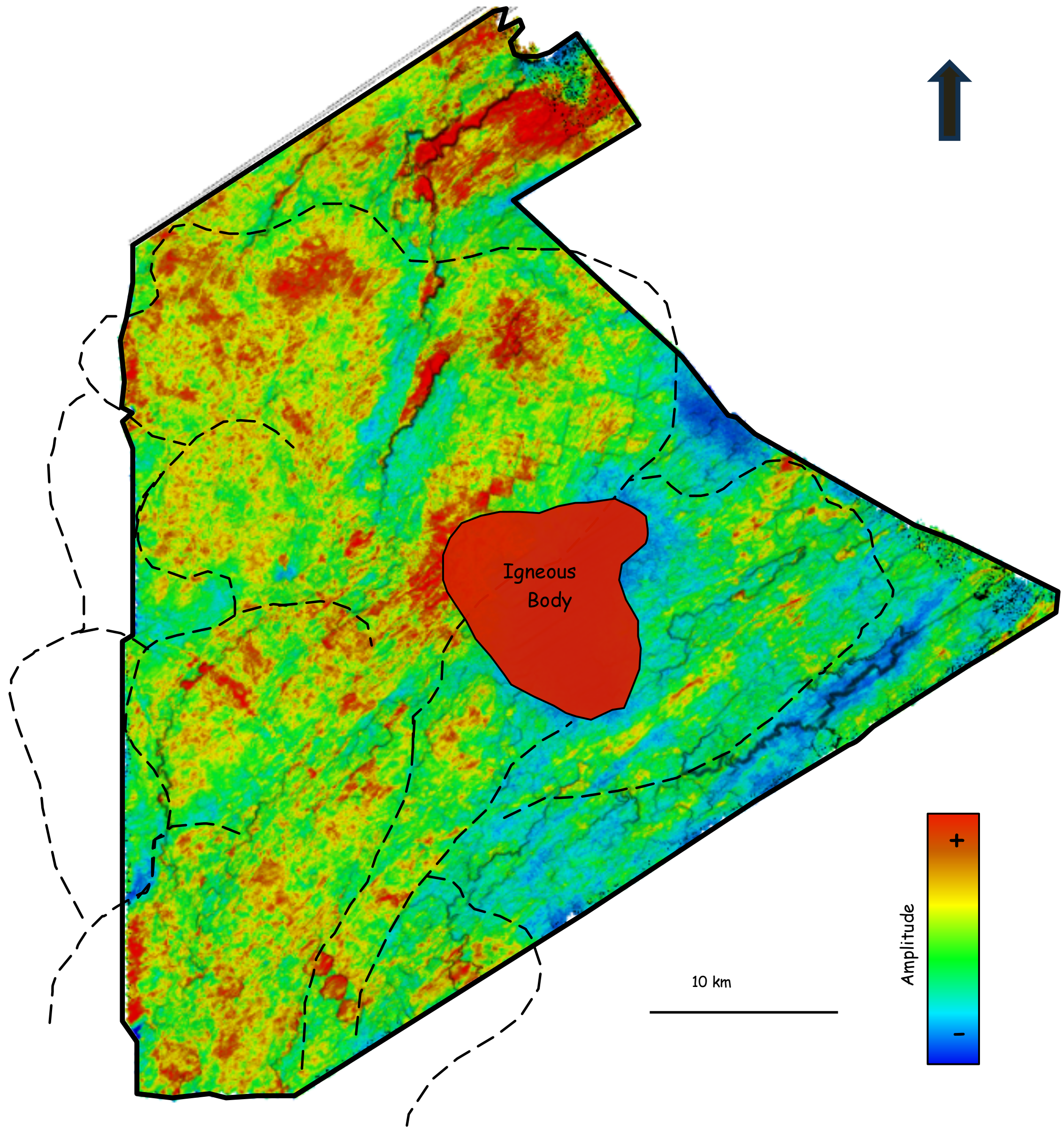



Figure 4.7: Distribution of the Middle Miocene submarine fan deposits as appears in this windowed amplitude extraction map from base of the Moki Formation to 90 ms up.

## 4.3 DEVELOPMENT OF THE MIDDLE MIOCENE SUBMARINE FAN DEPOSITS

The recorded thickness of the Moki Formation in the wells and seismic sections as well as the multiple lobes existence in the investigated thickness maps, leads to the question: How did ~ 300 m thick of submarine fan deposits stack and develop?

Judging from the seismic attribute maps, three major shifts happened in the path of the submarine fan development. The seismic interpretation technique that aid in exploration of advancement of these lobes was stratal-slicing. According to Zeng (2010), stratal-slicing technique can be done by selecting two reference surfaces and slicing between them proportionally. Following this technique, I chose the base and top of the Moki Formation as reference surfaces and generated 20 slices between the top and the bottom of the Moki Formation. One of the restrictions of this technique, in order to get precise results, in a seismic geomorphology perspective, is that the in-between reflectors should be sheets. Considering the work scale of this study and objective for using this technique, which was defining the depocenters as submarine fan develop within the whole range of the Moki Formation, I omitted perfect flat-lying conditions.

Amplitude extraction on each of the 20 surfaces shows variation in high amplitude spots position as the deposits grow though time. From bottom to top, the most noticeable changes were recognized in the 2$^{nd}$, 11$^{th}$, and 19$^{th}$ slices (fig. 4.8). By taking into account the age duration of the Moki Formation (17-12 Ma, according to King and Thrasher, 1996) the whole formation was deposited in 5 Ma. In the early stage of the

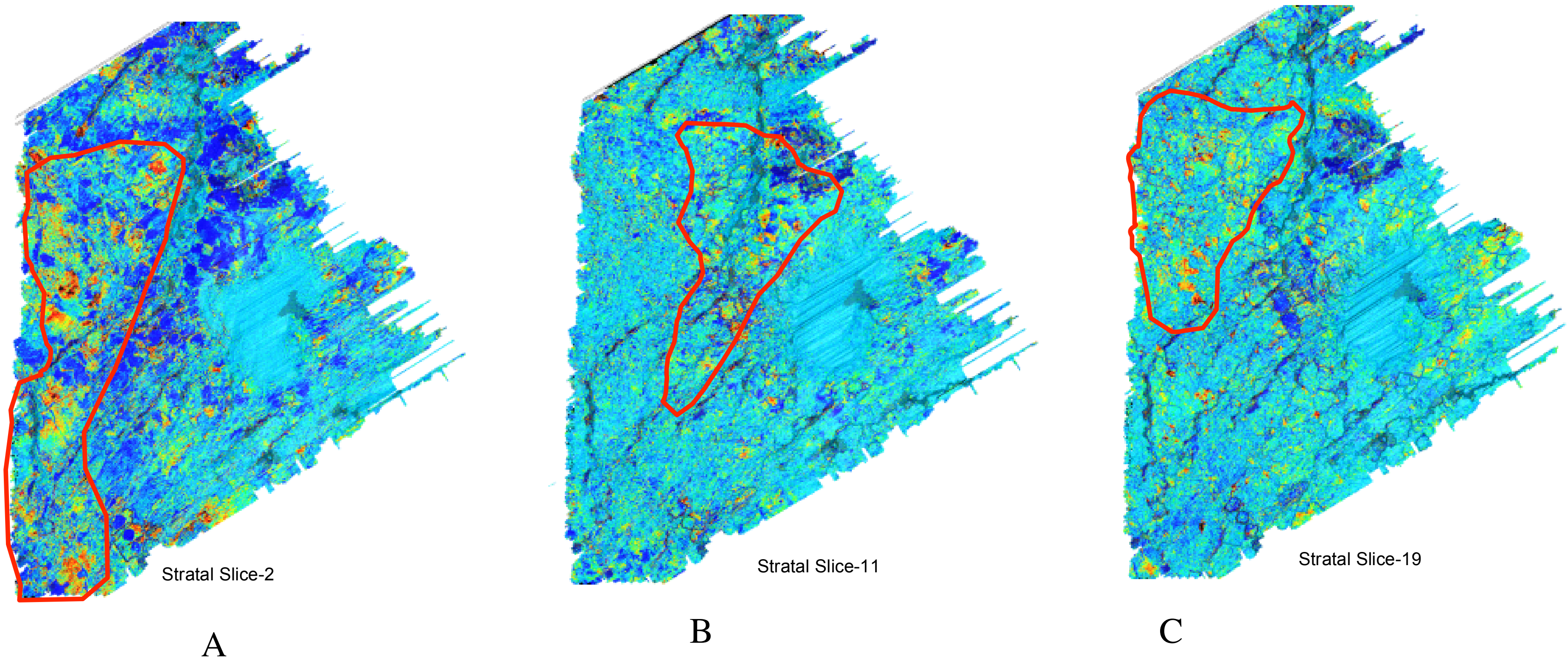



Figure 4.8: Development stages of the Middle Miocene submarine fan. A. Northward progradation, B. NE avultion, C. NW avulsion.

submarine fan development about 16.5 Ma, the sediments deposited and prograded northward and then shifted toward northwest by 14 Ma, then migrated to the north and northwest again at the end of the depositions stage by 12 Ma ago.

The last stage of Moki submarine fan deposition was toward north and northwest that indicated by high amplitude location, and corresponds to the same direction of the paleochannels that was detected in the same part of this study where their downstream direction was toward NW.

Outline comparison of the inferred development stages, generally gives the same outline of the submarine fan lobes that resulted from the amplitude extraction map for the whole range of the Moki Formation (fig. 4.9).

The expected reason for this pattern of change of this first northward then NE later NW and each farther from previous location, could be because at the beginning of the deposition the sediments moved northward with out restrictions then when the amount of deposited sediments became greater, the sediments themselves blocked the progradation path and shifted toward the NW and later by the same mechanism it moved to N and NW.


Figure 4.9: Comparison of the individual submarine fan development stages with the outline of the overall submarine fan deposits in the study area.

# Chapter Five: Forties Submarine Fan System; An Analogue Example From North Sea, UK

## 5.1 Introduction

Similarities of the Forties submarine fans in the North Sea with the Moki Middle Miocene submarine fans in the Taranaki Basin presents a significant confirmation of the interpretation of Taranaki submarine fans. Integrating well log and seismic data with core data have reveled many details about submarine fans in North Sea. Comparison between the extensively investigated submarine fans of the North Sea that have been in production since 1970, with the relatively less investigated submarine fans in the northern Taranaki Basin can be a significant checking tool for the interpretation.

## 5.2 Submarine Fans in North Sea, UK

During the Paleogene, the Atlantic sea floor spreading and Thulean volcanism led to rise of British Isles with a slope toward southeast. Consequently, several submarine fans were deposited in North Sea. The stratigraphic succession from Late Paleocene to Late Eocene includes several submarine fan deposits like the Andrew, Forties, Rogaland, Frigg, Tay, Alba, and Alba North fans (Den Hartog Jager et al., 1993). The Forties submarine fan system provides a resemblance to the Middle Miocene submarine fan in the northern Taranaki basin is. Due to the existence of many wells (more than 100) and seismic data about the Forties submarine fan, especially in Forties oil field, the understanding about Forties fan system is well understood.

### 5.3 FORTIES SUBMARINE FAN, NORTH SEA, UK

The submarine fan of the Forties, deposited during the Late Paleocene, comprises a large turbidite reservoir. The Forties sandstone deposits are located offshore Scotland in UK, while originated from the northwest area of the Shetland's uplifted part (Hempton et. al., 2005) (fig. 5.1). The Forties fan is composed dominantly of sandstone with a minor portions of shale and represent the middle and lower part of the submarine fan complex.

Hill and Wood (1980) stated that grain flow, debris flow, and turbidity currents were responsible for the sediment transport and deposition. The Forties submarine fan is subdivided into interbeded sandstone, shale and limestone in its lower part and a principal sandstone at the top (Hill and Wood, 1980). Up to 2005, the Forties field has produced about 2.4x109 BBO cumulatively. As a result of new technology and more concise characterization of the field, the recovery factor changed from 20% in 1970, to 62% in 2005.

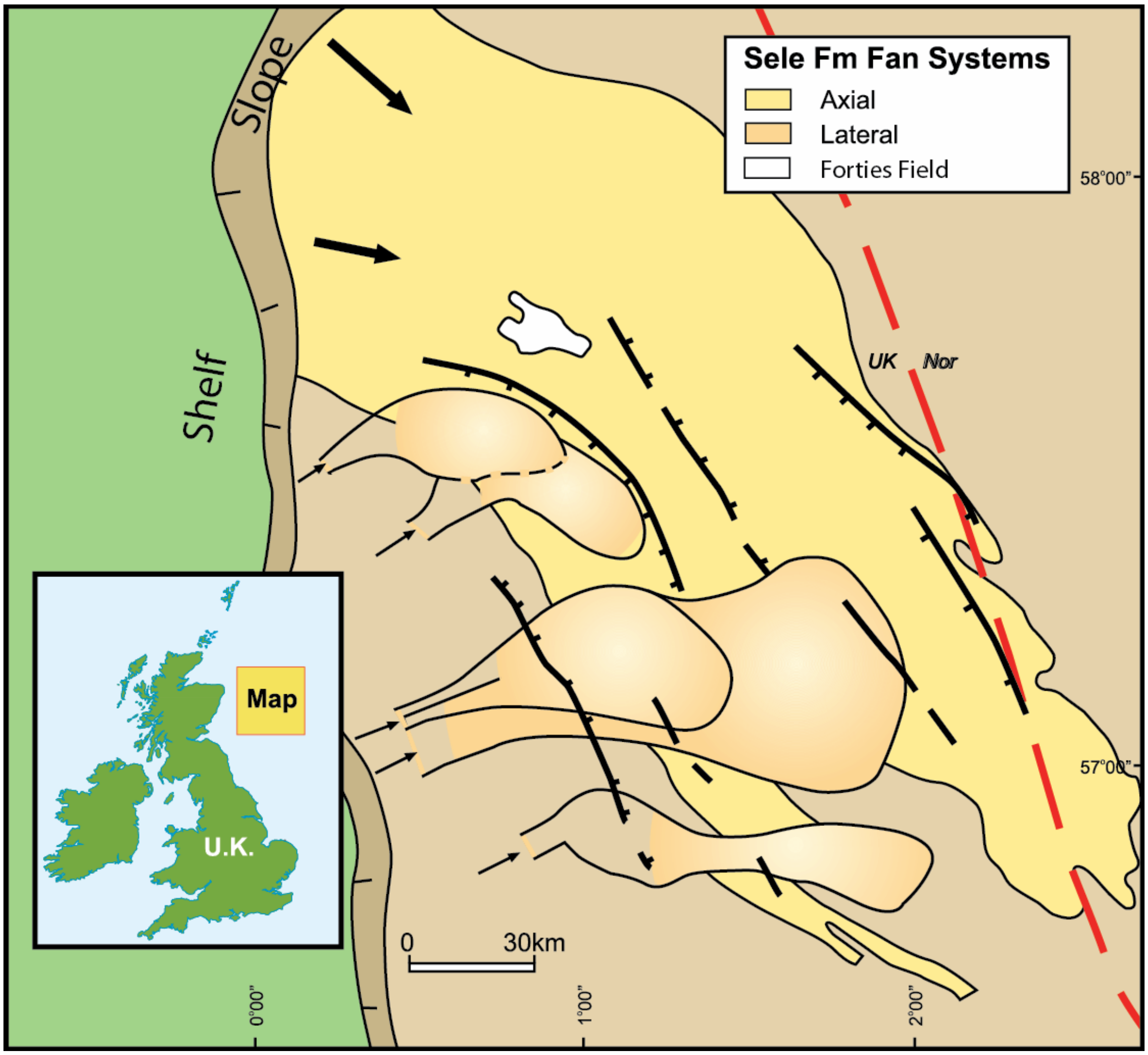



Figure 5.1: Location of Forties field within Sele Formation submarine fan system, North Sea, UK (after Hempton et al., 2005).

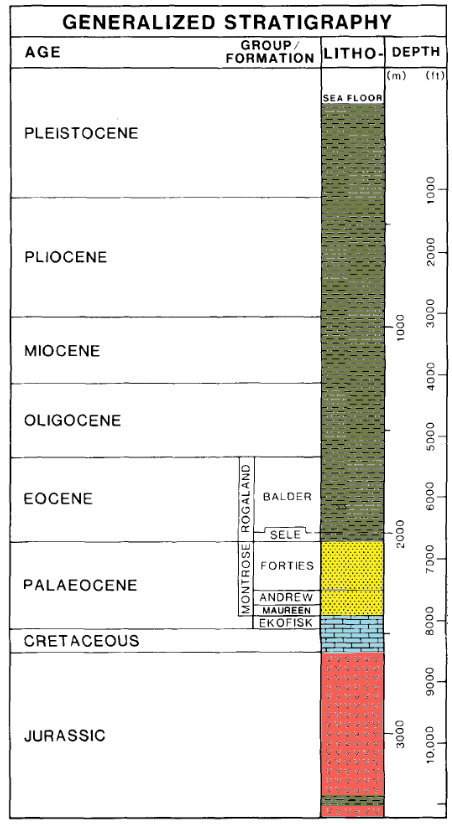
## 5.4 GEOLOGY OF THE AREA

The basement rock consists of Middle Jurassic volcanic rocks accompanied by minor sedimentary rocks. The Kimmeridge Clay Formation mainly comprised of silty mudstone and siltstone overlies the volcanic rocks. The base of the Cretaceous is characterized by a regional unconformity followed by a condensed section of mudstone and sandstone. The Upper Cretaceous section consists of a massive chalk with marl rocks. In the early Tertiary, the late Cretaceous and the early Paleocene pelagic carbonate deposition changed to clastic components, with a large sediment thickness of deltaic, shelf, and submarine fan environment (Stewart, 1987).

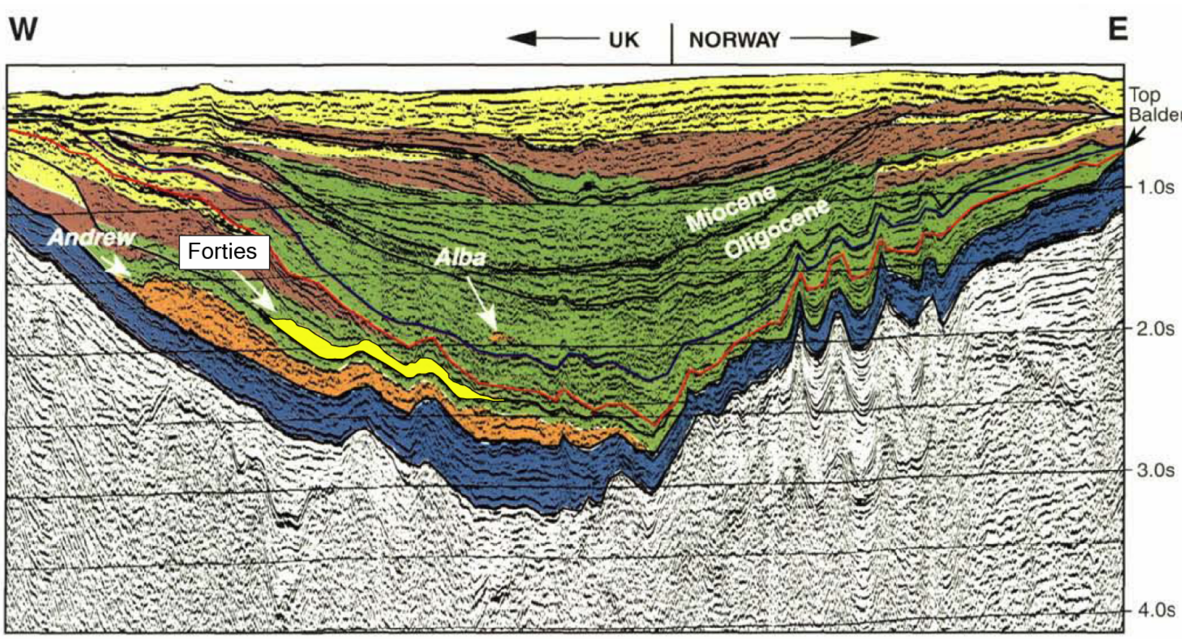
The structural styles existing during the Tertiary governed the depocenters locations and led to deposition of sediments in an elongate NW-SE direction across the Mesozoic graben (Wills, 1990) (fig. 5.2). As the deposition of the large clastic budget occurred during the Late Cretaceous, which associated with the uplift of the northwestern part of North Sea, the sandstones of the Forties Member aligned toward the central graben with a source from the NNW. By the end of the Paleocene, relative sea level began to rise, resulting in deposition of a regional mudstone in the area (Wills, 1990).

During the Eocene, due to relative sea level oscillations, several alternating marine mudstone and sandstone depositional events occurred as a result of the sea level lowstand and highstand. From the Late Eocene to the Holocene, mudstone covered the whole basin and became the dominant deposits (Wills, 1990).

Figure 5.2. A: Stratigraphic succesion of sediments in Forties field (after Wills, 1991). B. Forties submarine fan deposits as appears in a seismic line across North Sea (modified from Den Hartog Jager et al., 1993).




A




B

## 5.5 SEDIMENTARY FACIES AND WELL LOG ANALYSIS

Availability of wells in the Forties field help in providing information from cores and logs, consequently has led to a good understanding of the depositional environment of Forties submarine fan in North Sea. Hill and Wood (1980) identified five diagnostic log patterns: constant high gamma ray, erratic pattern, upward decreasing gamma ray, constant low gamma ray, and upward increasing gamma ray (fig. 5.3). Integration of these log data with the lithological facies interpretation form core analysis, led to a better constraint of depositional environment definition.

The interpreted depositional settings supported by the well logs include lower fan shale, channel sand at the base, prograding lobes, then changing again to channel sand, and lower-fan's shale and sand. More studies on the reservoir characterization in the Forties field supported by seismic and subsiesmic approaches, provided four sedimentary faices association: amalgamated sandstone facies, heterolithic, hemipelagic mudstone, and deformation zones that associated with faults (Hempton et al., 2005). The log pattern interpreted as the base of the Bouma sequence, has a continuous high gamma ray reflection. This section is mainly formed from the grey and waxy green shale with marine fauna and flora. This hemiplegic mud probably reflects the lower-fan or the basin plain.

The irregular gamma ray pattern represents the alternated sandstone and shale. Hill and Wood (1995) argued that if this variable motif, associated with channelized sediments, reflects the levee and interchannel setting whereas if it lacks a channelized section it reflects lower-fan facies.

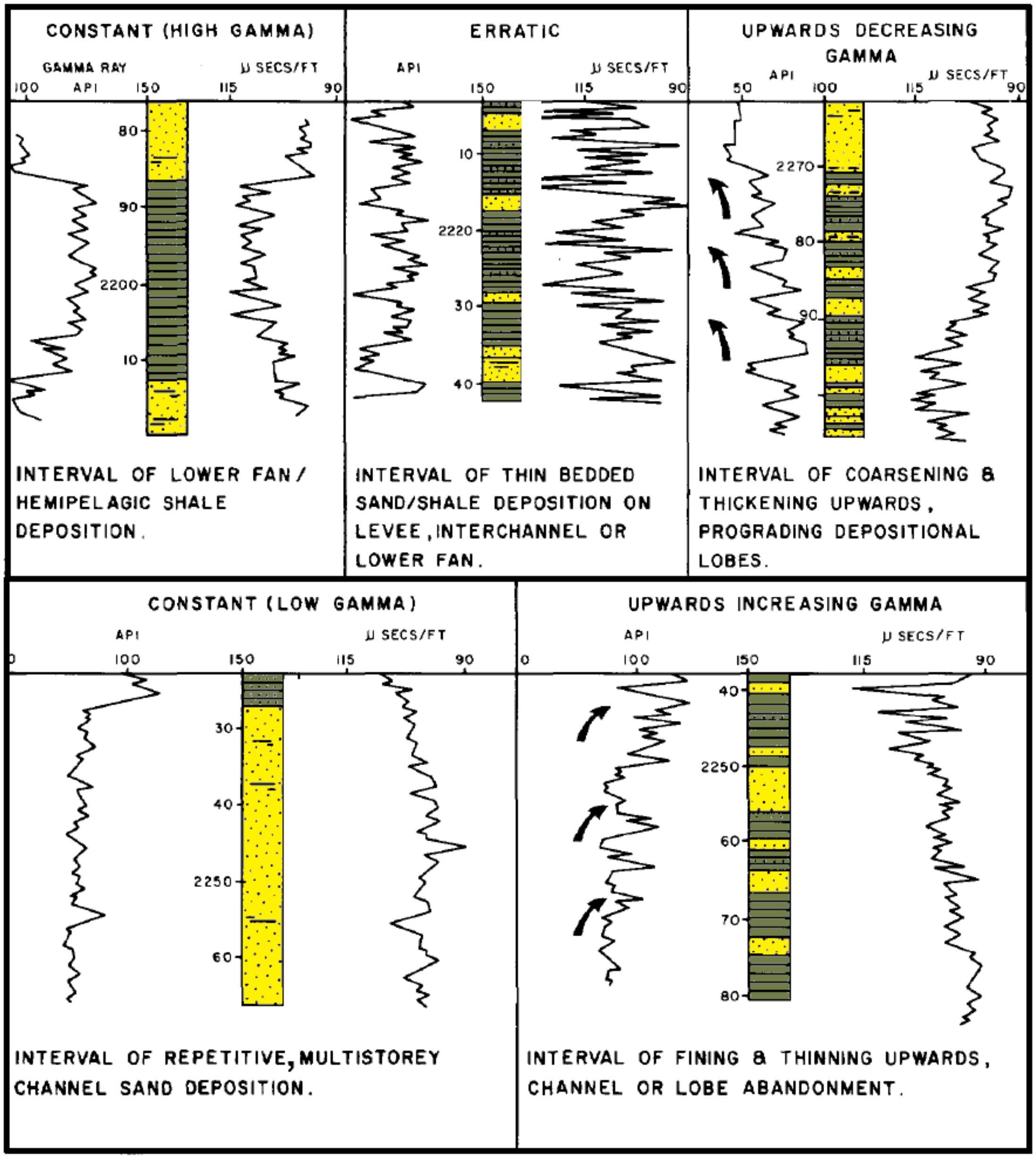



Figure 5.3: Well logs motif of Forties submarine fan and their interprettionan (after Hill and Wood, 1980).

The upward decreasing gamma ray, which means less radiation and less clay content, indicates channels presence with sandstone dominance. The sediments in this interval are poorly sorted of medium and fine grain size (Hill and Wood, 1995). The cores show coarse-grained lamina, graded bedding, convolute bedding, and sole marks. These evidences enhanced the interpretation of the sedimentary facies as amalgamated channels. The steady low gamma ray motif reflects large content of sandstones and the core analysis verified occurrence of conglomerates and pebbly sandstone about 20 m thick. Between the amalgamated channels, thin beds of shale are recognized. In general, the environment for these features in the logs and cores are interpreted as a channel deposits. The last recognized log patterns marked by upward increasing of gamma ray, accordingly, the dominance of shale. The increasing gamma ray associated with increasing sonic log motif and decrease of density and resistivity logs. As this section overlies a channelized section, the increasing gamma ray indicates the abandonment of the feeding channel for the submarine fan lobe.

## 5.6 DEPOSITIONAL ENVIRONMENT

Depending on the logs, cores and the geologic setting of the Forties submarine fan and other reservoir characterization studies many aspects of the fan development and geometry were clarified. The Forties submarine fan was deposited during the Late Paleocene (Den Hartog Jager et al, 1993; Wills, 1991; Hempton et al., 2005), which is the time when the northwestern part of the Shetland platform was elevated with association of sea floor spreading of North Atlantic (Ziegler, 1978). The Forties submarine fan constitutes one of several submarine fans that all belong to a major submarine fan sequence of the Sele Formation (Wills, 1991; Hempton et al, 2005) that derived from NW.

The Sele Formation, which is formed by turbidity currents, belongs to two different sources of sediments, from NW and E. The Forties field is originated from the sediments that came from the NW with an extension to about 300km and 100 wide (Hempton, 2005). As the Forties field location is much closer to the sediments source form the NW than the other submarine fans in the adjacent area, the thickness of the Forties fan is about 260 m and becomes less toward the S and the SE to about 137 m as in Pierce field.

The cores and the logs in the Forties field revealed the presence of several facies that suggest the environment of deposition to be middle fan (Den Hartog Jager et al, 1993; Hill and Wood, 1980). The dominantly shale units mixed with siltstone are considered to be lower fan deposits. The medium to coarse grain size with an abrupt change in its base and sedimentary structures, suggests channel sands. These filled channels was followed by progradation of the lobes that are distinguished by several sections of up ward coarsening size of grains to about 35 m and mixed with thin shales. These distinctive faces evidence the middle fan environment in the NE and middle to lower fan in the SE area of the field with less sand content (Hill and Wood, 1980). Channels in Forties submarine fan recognized in cores by well-sorted medium to coarse sands associated with sedimentary structures. Overall, the submarine fan deposits that are closer to the source have more sand content with large grain size, greater thickness, and hosts more paleochannels (fig. 5.4) than deposits in the distal area (Hempton et al., 2005).

The seismic interpretation of the Forties submarine fan also shows channels (fig. 5.5) on the upper part of the deposits and they appear in a NW-SE direction, which is the trend of the sediments that originated form the Shetland platform in the N and NW of the Forties field (Den Hartog Jager et. al., 1993).

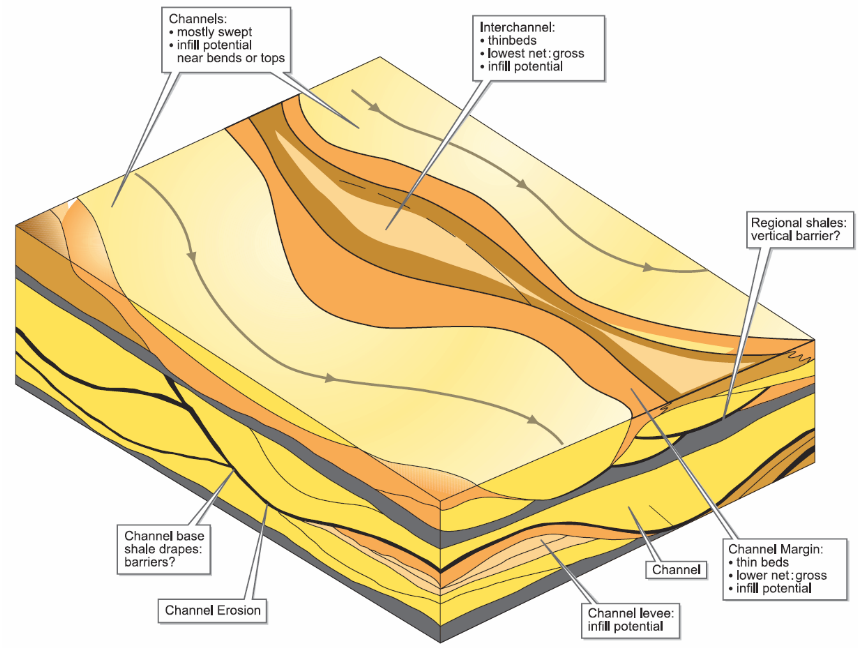



Figure 5.4: A propsed model for the proxial area of the Sele Fn. that includes Forties fan depostis (from Hempton et al., 2005).

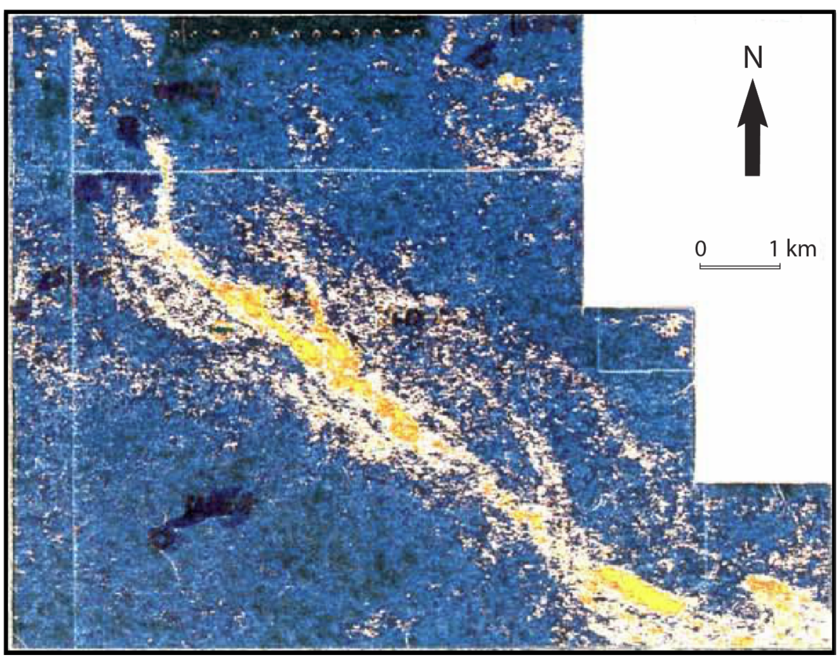



Figure 5.5: A channel complex in the Forties field as apear in a windowed amplitude extractio map. The main channel trends NW-SE (from Den Hartog Jager et al., 1993).

# Chapter Six: Discussion and Conclusions

## 6.1 Discussion

The analogy of tectonic history, geologic setting, well logs motifs, and depositional environments show that submarine fan systems in both in the Taranaki Basin and in the North Sea were deposited in a basinal setting dominated by mud. Then, fall of relative sea level triggered sediment influx into the basin and led to deposition of the submarine fans. As the deposition continues, channel belts and avulsions established. The development of the basin floor fan lobes. Changing the direction of channels led to incision of the previous existed lobes and depositing channel levee sediment on the previous site. This pattern can be repeated as far as sediment budget available and eventually, dominance of shale and mudstone again.

This postulated image can be verified by the well logs and core clearly, the interpretation of the logs of the Forites field correspond to the core data as decrease in gamma ray comparable with channel-related sedimentary structure.

So, emerging variable data together will led to better visualization of the basin floor fan characteristics. In case of lacking sufficient information, comparison with similar cases will reduce uncertainty of the interpretation and provide more evidence and consequently a more enhanced depositional model.

## 6.2 CONCLUSION

The Middle Miocene submarine fan deposits of the Moki Formation originated from south and prograded toward north with lateral distribution within 40 km in east-west direction according to the Parihaka 3D seismic survey location in northern Taranaki Basin (fig. 5.1). The explored submarine fan deposits reflect the middle fan setting which is well developed in the northern part on the Western Stable Platform. The gamma ray motif displays progradation, aggradation and retrogradation of submarine fan deposits as they evidence sandy deposits introduction on a muddy basin floor then sand dominance and at the end increase of basin floor mud amount. Two paleochannels are recognized on the northwestern part, with flow direction toward NW; they incise the mounded lobes as indicated by the seismic sections. These paleochannels represent the upper part of the deposits and they relate to the last stage of submarine fan development. The channelized part of the lobes in the study area shows the greatest thickness and it is about 400 m. The thickness becomes less toward the flanks of the submarine fan deposits as indicated by the well data, with an average thickness of the submarine fan deposits across the area of about 300 m.

The Middle Miocene Moki Formation submarine fan deposits were developed and distributed in the northern Taranaki Basin by three major shifts in their path. First, progradation was northward for about 0.5 Ma then shifted to NW for about 2.5 Ma and later migrated to the NNW for about 2 Ma.

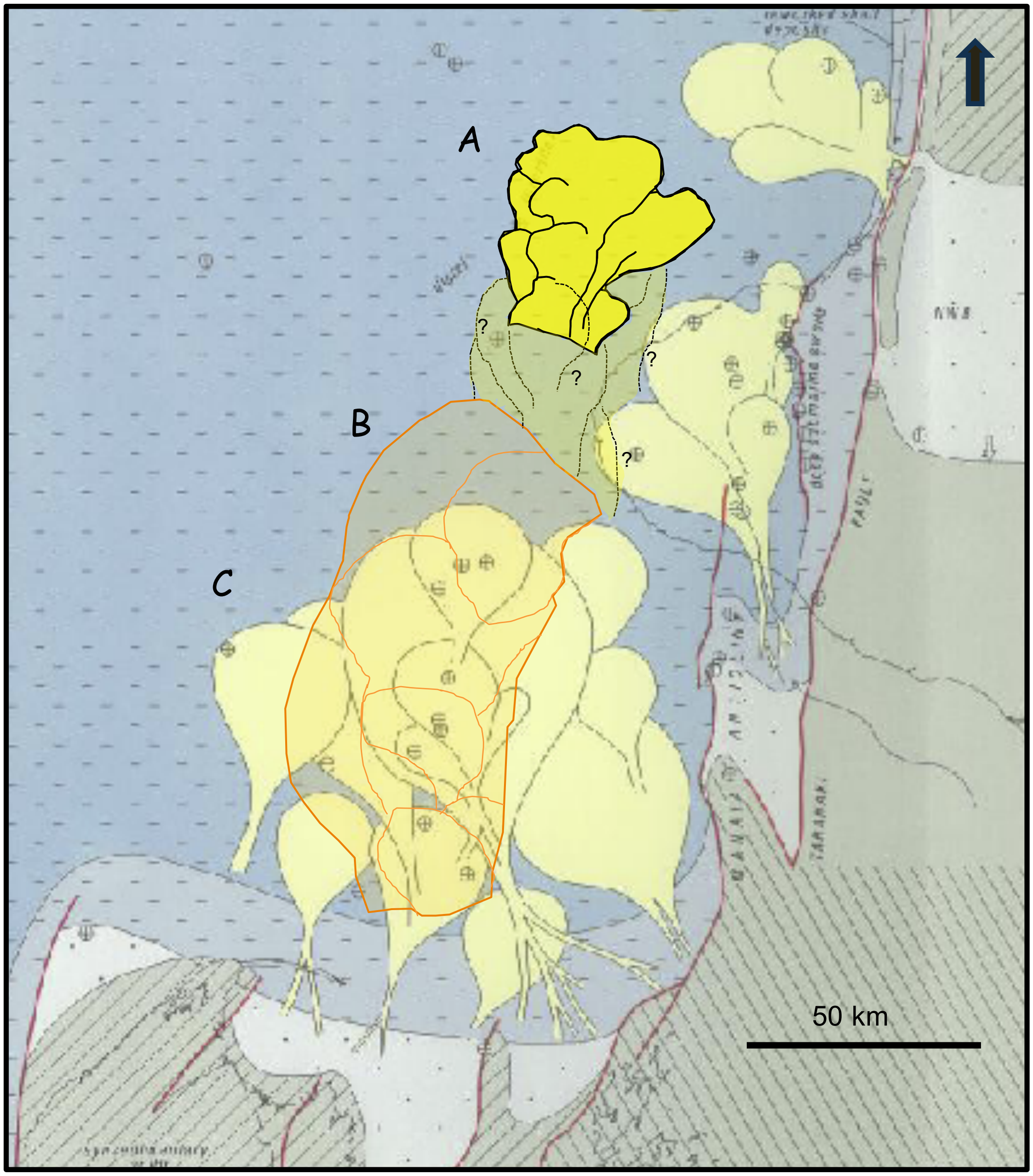



Figure 6.1: Paleogeographic map of the Middle Miocene. A. The explored ancient submarine fans by this study. B. Interpretation done by Grain, (2008). C. Interpretation done by King and Thrasher, (1996). The map modified from King and Thrasher, (1996).

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